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THE INFLUENCE OF THE WIND ON THE ERROR AND PROBABILITY OF LOCALIZATION

Centre National d'Etudes Spatiales

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Memorandum 7/65

THE INFLUENCE OF THE WIND ON THE ERROR AND PROBABILITY OF LOCALIZATION.

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Ecole Nationale Superieure
de l'Aeronautique, Centre
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INFLUENCE OF THE WIND ON ACCURACY OF LOCALIZATION

Since the balloons travel with the air flow, the influence of the wind will cause a systematic error of localization. The reason for this is analogous to that disclosed in the examination of errors due to the rotation of the earth (there is also an analogy between the rotation of the earth and a west-east wind).

However, the problem here is different and poses new problems. It was shown that, since the rotation of the earth during the interval between interrogation is known, an iterative process of correction permits accurate compensation for this influence and very rapidly furnishes accurate localization.

By contrast, when wind is present, the displacement B_1B_2 of the balloon during the interval between interrogation is unknown due to the random components of the wind.

In regard to correction of the errors due to continuous components, it poses the further problem of the determination of the interval of time necessary for their determination.

/

1.1 - Wind parallel to the trace:

The two positions S_1 and S_2 of the satellite separated by the interval between interrogation T_1 are established in relation to the mean position B_m of the balloon at the orbital latitude phi (cf. fig. 1).

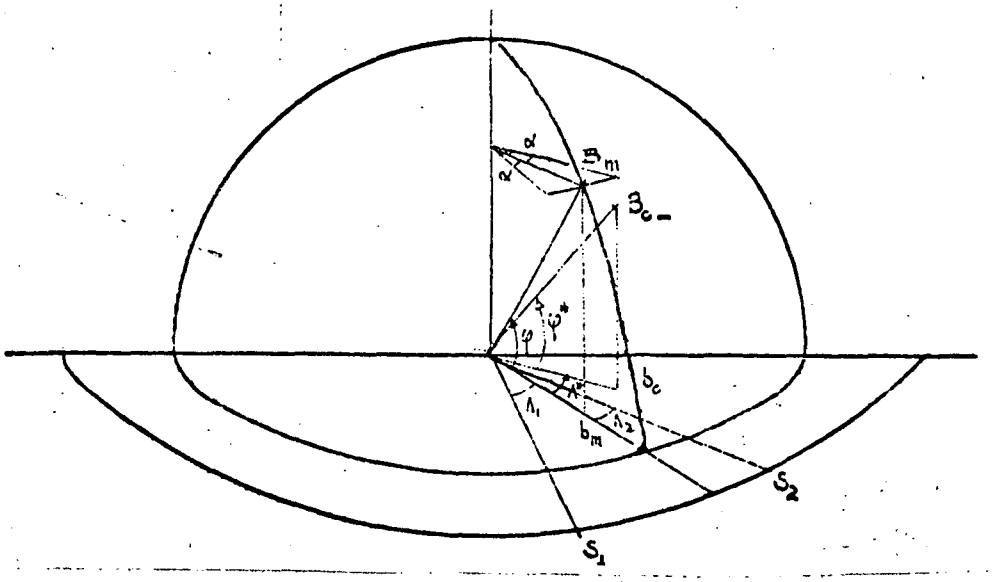


Fig. 1

If v_h is the speed of the wind and R* is the radius of the balloon sphere, then the angle 2α separating the balloons B_1 and B_2 is equal to

$$v_h T = R^* \cos\varphi \times 2\alpha$$

or

$$\alpha = \frac{v_h}{R^* \cos\varphi} \frac{T}{2} \qquad (1)$$

The measured distances d_1 and d_2 are therefore such that

$$d_1^2 = R^{*2} + R_s^2 - 2 R R_s \cos\varphi \cos(\Lambda_1 + \alpha) \qquad (2)$$
$$d_2^2 = R^* + R^2_s - 2 R R_s \cos\varphi \cos(\Lambda_2 - \alpha)$$

Localization of the balloon, on the basis of the positions S_1 S_2 and the distances $d_1 d_2$, furnishes a position B_c (ϕ^*, λ^*) such that

$$\operatorname{tg}\Lambda^* = \frac{D_2 \cos\Lambda_1 - D_1 \cos\Lambda_2}{D_1 \sin\Lambda_2 - D_2 \sin\Lambda_1} \qquad (3)$$

and $$\cos\varphi^* = \frac{D_1}{\cos(\Lambda^* - \Lambda_1)} \qquad (3)$$

with $$D_1 = \frac{R^{*2} + R_s^2 - d_1^2}{2RR_s^*} \text{ and } D_2 = \frac{R^{*2} + R^2_s - d_2^2}{2 R^* R_s} \qquad (4)$$

The errors of latitude are therefore $\phi^* - \phi$ and of longitude λ^* or in km $R^* (\varphi^* - \varphi)$

$R \cos\varphi . \Lambda^*$

and the overall error

$$E = R \sqrt{(\Lambda\varphi)^2 + (\cos\varphi . \Lambda^*)^2} \qquad (5)$$

For symmetrical bases, we again find that the error of longitude ($\lambda_2 = \lambda_1$) is zero and the localization is falsified exclusively for latitude.

1.2 - Wind perpendicular to the trace (South-North):

If $V_\perp$ is the speed of the wind, the variation of latitude 2β of the balloon during the interval of interrogation is (cf.fig. 2)

$$R^* \cdot 2\beta = V_\perp T$$

or

$$\beta = \frac{V_\perp}{R^*} \cdot \frac{T}{2} \qquad (6)$$

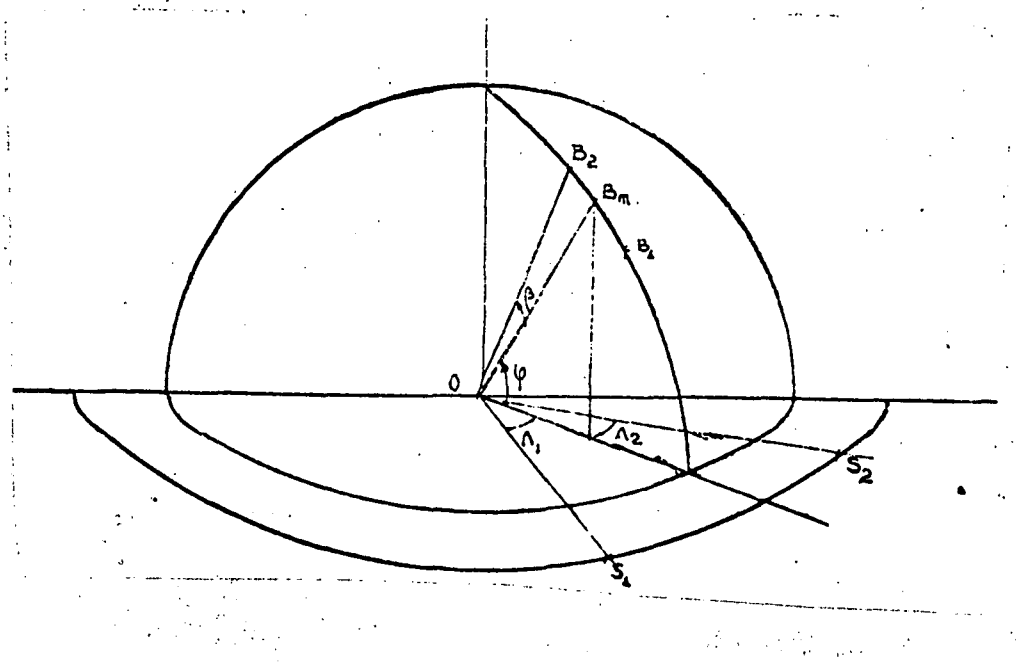


Fig. 2

The measured distances d_1 and d_2 are:

$$d_1^2 = R^{*2} + R_s^2 - 2R^*R_s \cos\Lambda_1 \cos(\varphi - \beta)$$
$$d_2^2 = R^{*2} + R_s^2 - 2R^*R_s \cos\Lambda_2 \cos(\varphi + \beta) \qquad (7)$$

The localization of the balloon, on the basis of the positions S_1 S_2 and of the distances d_1 d_2, furnishes a position B_c (ϕ^*, λ^*) given by formulas 3 and 4 where d_1^2 and d_2^2 are now given by equ. 7 which replaces equ. 2.

1.3 - Indeterminate Wind

The wind is assumed to be known by its two components v_h and v_h and v_i, respectively parallel and perpendicular to the trace (cf. fig. 3)

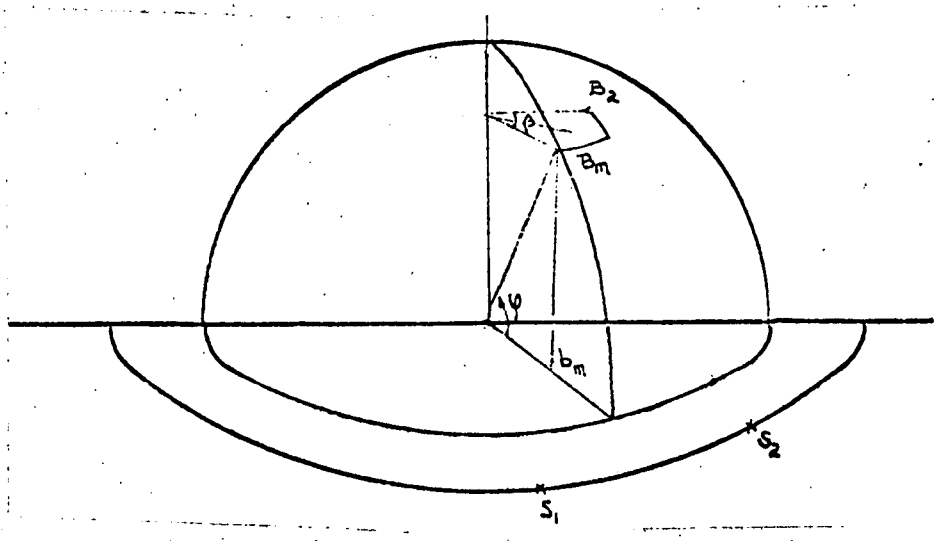


Fig. 3

As a first approximation (Note: The variation of longitude actually so determined is only a mean value due to the variation of latitude ϕ of the balloon under the influence of the wind perpendicular to the trace), if the angle β is sufficiently small to introduce a negligible variation of latitude of the balloon, we can express the distances d_1 ($S_1 B_1$) and d_2= ($S_2 B_2$) in the form:

$$d_1^2 = R^{*2} + R_s^2 - 2 R^* R_s \cos(\varphi - \beta) \cos(\Lambda_1 + \alpha)$$

and

$$d_2^2 = R^* + R_s^2 - 2 R^* R_s \cos(\varphi + \beta) \cos(\Lambda_2 - \alpha) \quad (8)$$

The same formulas can then always be utilized.

If the wind is not parallel to the trace for an infinitely small time dt and if ϕ_m and λ_m are the coordinates of the balloon B_m, we have

$$d\varphi = \frac{v_\perp}{R^*} dt \qquad \Lambda' = \frac{d\theta}{dt} = \frac{v_\parallel}{R^* \cos\varphi}$$

$$\Lambda = \Lambda_m + \frac{v_\parallel}{v_\perp} \left[\operatorname{arg\,th} \sin\varphi \right]_{\varphi_m}^{\varphi}$$

At the time T/2, we will therefore have the position B_2 of the balloon

$$\varphi_{B_2} = \varphi_m + \frac{v_\perp}{R''} \frac{T}{2}$$

$$\Lambda_{B_2} = \Lambda_m + \frac{v_h}{v_\perp} \left[\operatorname{arg\,th} \sin\varphi_{B_2} - \operatorname{arg\,th} \sin\varphi_m \right]$$

$$\frac{v_\perp}{v_h} (\Lambda_{B_2} - \Lambda_m) = \operatorname{arg\,th} \sin\varphi_{B_2} - \operatorname{arg\,th} \sin\varphi_m$$

$$\operatorname{th} \frac{v_\perp}{v_h} (\Lambda_{B_2} - \Lambda_m) = \frac{\sin(\varphi_m + \beta) - \sin\varphi_m}{1 - \sin(\varphi_m + \beta) \sin\varphi_m} \qquad \beta = \frac{v_\perp}{R} \frac{T}{2}$$

$$\operatorname{th} \frac{v_\perp}{v_h} (\Lambda_{B_2} - \Lambda_m) = \frac{2 \sin\frac{\beta}{2} \cos(\varphi_m + \beta/2)}{1 + \frac{1}{2}\left[\cos(2\varphi_m + \beta) - \cos\beta \right]}$$

$$\Lambda_{B_2} - \Lambda_m = \frac{v_h}{v_\perp} \operatorname{arg\,th} \frac{2 \sin\frac{\beta}{2} \cos\left(\varphi_m + \frac{\beta}{2}\right)}{1 + \frac{1}{2}\left[\cos(2\varphi_m + \beta) - \cos\beta \right]}$$

at the limit if $v_\perp \to 0$ $\quad \beta \to 0$

By limiting ourselves to the first terms of the development

$$\Lambda_{B_2} - \Lambda_m \to \frac{v_h}{v_\perp} \operatorname{arg\,th} \frac{\beta \cos\varphi_m}{\frac{1}{2}\left[\cos 2\varphi_m + 1 \right]}$$

$$\to \frac{v_h}{v_\perp} \operatorname{arg\,th} \frac{2\beta \cos\varphi_m}{2\cos^2\varphi_m} \quad \simeq \frac{v_h}{v_\perp} \frac{\beta}{\cos\varphi_m}$$

$$= \frac{v_h}{R \cos\varphi_m} \frac{T}{2}$$

we again find the preceding results.

In other words, for a wind of indeterminate direction and given amplitude and when we know the components of the wind in accordance with a meridian and a parallel (inertial), the preceding formulas must be corrected for a wind not parallel to the trace. We will always have

$$d_1^2 = R^{*2} + R_s^2 - 2 R^* R_s \cos(\varphi - \beta) \cos(\Lambda_1 + \alpha_1) \quad (9)$$

$$d_2^2 = R^{*2} + R_s^2 - 2 R^* R_s \cos(\varphi + \beta) \cos(\Lambda_2 - \alpha_2)$$

avec $\beta = \frac{v_\perp}{R} \frac{T}{2}$ et $\alpha_2 = \frac{v_\perp}{v_\perp} \operatorname{arg\,th} \frac{2\sin\frac{\beta}{2}\cos(\varphi_m + \frac{\beta}{2})}{1+\frac{1}{2}\left[\cos(2\varphi_m+\beta)-\cos\beta\right]}$

et $\alpha_1 = \frac{v_h}{v_\perp} \operatorname{arg\,th} \frac{2\sin\frac{\beta}{2}\cos(\varphi_m - \frac{\beta}{2})}{1+\frac{1}{2}\left[\cos(2\varphi_m-\beta)-\cos\beta\right]}$

2. CONTINUOUS WIND

2.1 - Wind parallel to the trace

The errors of localization due to wind parallel to the trace were calculated from formulas 1 to 5 in para. 1.1. In the annex will be found the computation program utilized to obtain the errors of localization in m.

- for orbital "latitude" Q_2 (1)

- for orbital "longitude" Q_3,
- for the overall error Q_4.

In the first part, it was also assumed that the vector of the wind is in the same direction as the vector of velocity of satellite displacement. The case where the directions of displacement are opposite will be considered in para. 2.1.5.

2.1.1 - Influence of position of bases:

The errors of localization considered here are defined as the difference between the mean position of the balloon during the interval of time t_i, $t_i + T$ and the calculated position of the balloon. Diagram 1 covers the case of an orbit of 900 km for wind parallel to the trace at 40 km/hr, and an interval between interrogation of 50 sec. where the mean position of the balloon is at 5° of the trace. We see that the error will be dependent to a considerable extent on the position of the base in relation to the mean position of the balloon since it may vary in the case under consideration by 25 km at the limit of visibility and by 100 m in the best case. It will also be noted that the error is essentially an error of latitude and the error of longitude remains limited and less than 5 km even in the most unfavorable case at the limit of visibility and is obviously zero for symmetrical bases.

It should also be noted that, if the configuration "symmetrical bases" corresponds to an extremum of error of localization, this extremum is not unique and does not even represent a minimum if the interval between interrogation is long.

This is shown more clearly in diagram 2 plotted under the same conditions as for diagram 1 but for an interval between interrogation of 400 sec. This phenomenon can be explained very easily:

Let us consider fig. (4) projected on the plane of the orbit parallel to OZ; the balloon is localized at the intersection of three spheres, i.e.)S_1 d_1) (S_2d_2(and the sphere of the balloons (B). The spheres (S_1) and (B) intersect along a circle in a vertical plane passing through B_1 and perpendicular to S_1 0 and the same holds for the spheres (S_2) and (B).

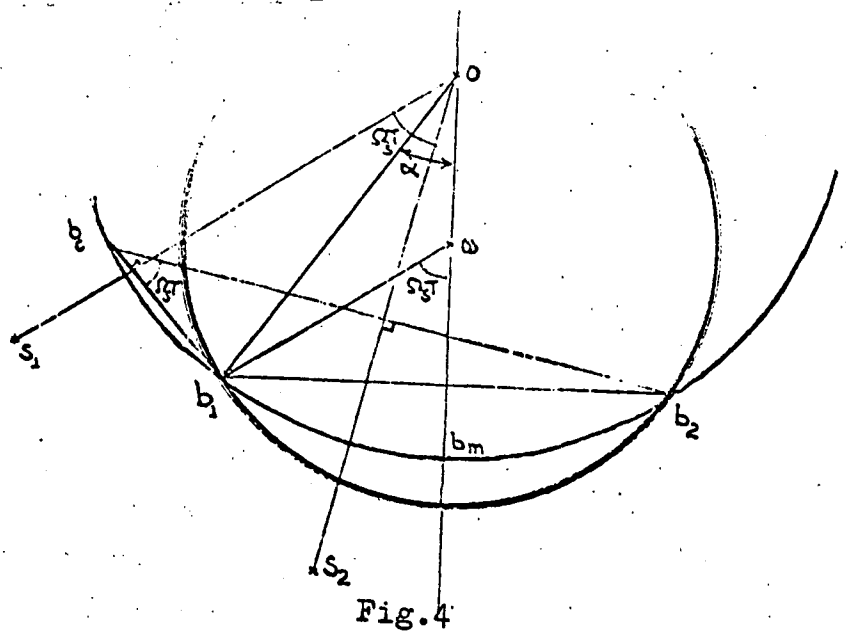
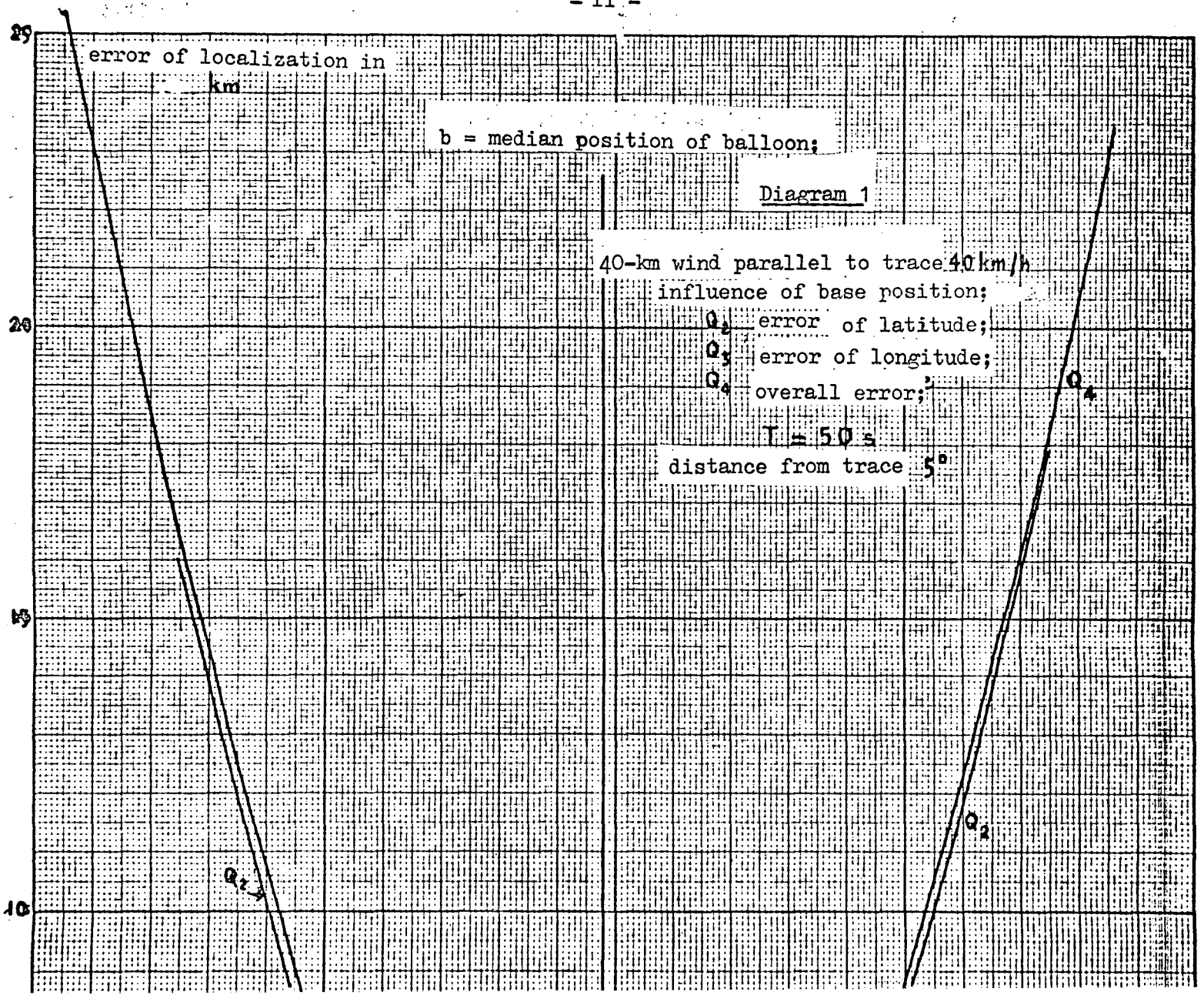
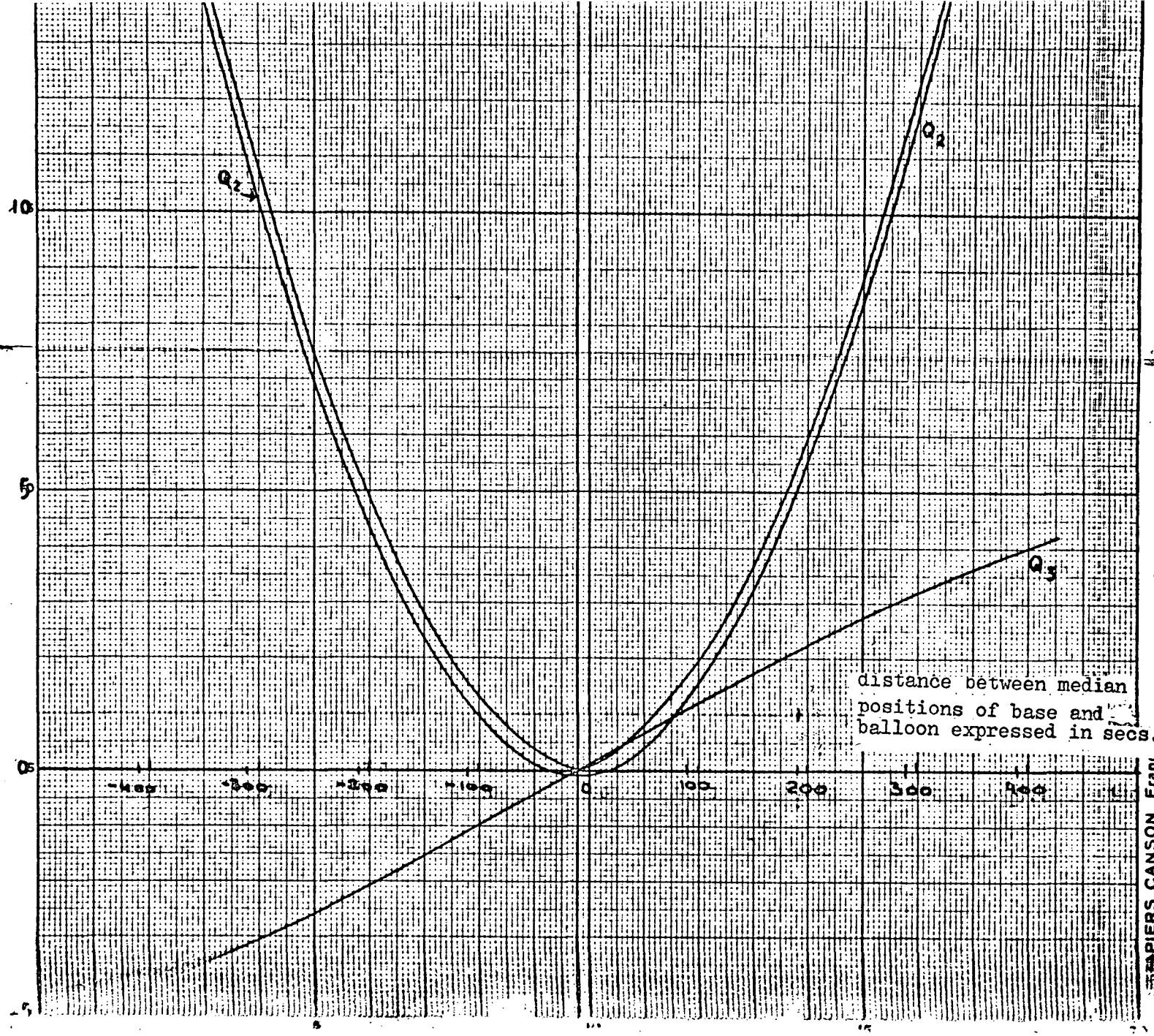


Fig.4


error of localization in km
b = median position of balloon;
Diagram 1
40-km wind parallel to trace 40 km/h
influence of base position;
Q_2 error of latitude;
Q_3 error of longitude;
Q_4 overall error;
T = 50 s
distance from trace 5°
Q_4
Q_2
Q_2


10
5
0.5
Q_2
Q_2
Q_3
-400
-300
-200
-100
0
100
200
300
400
distance between median positions of base and balloon expressed in secs.
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b_1 and b_c b_2 therefore together form an angle Ω_S T (cf.fig. 4) and b_c consequently lies on a circle Γ passing through $b_1 b_2$ which is the locus of the points from which $b_1 b_2$ is seen under the constant angle Ω_S T. The balloon B_c therefore is located at the intersection of the cylinder, with vertical axis and Γ as directrix, with the sphere of the balloons (cf.fig.5).

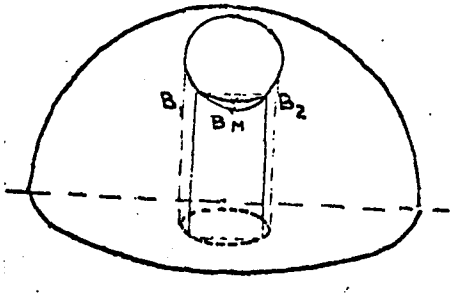


Fig. 5.

Let us examine this intersection and the development of the distance B_M B_c when λ varies (cf.fig.6)

Let ω be the center of the circle which is the locus of b_c. We then have $\widehat{b_1 \omega\ b_m} = \Omega_s T$ (1/2a angle in center).

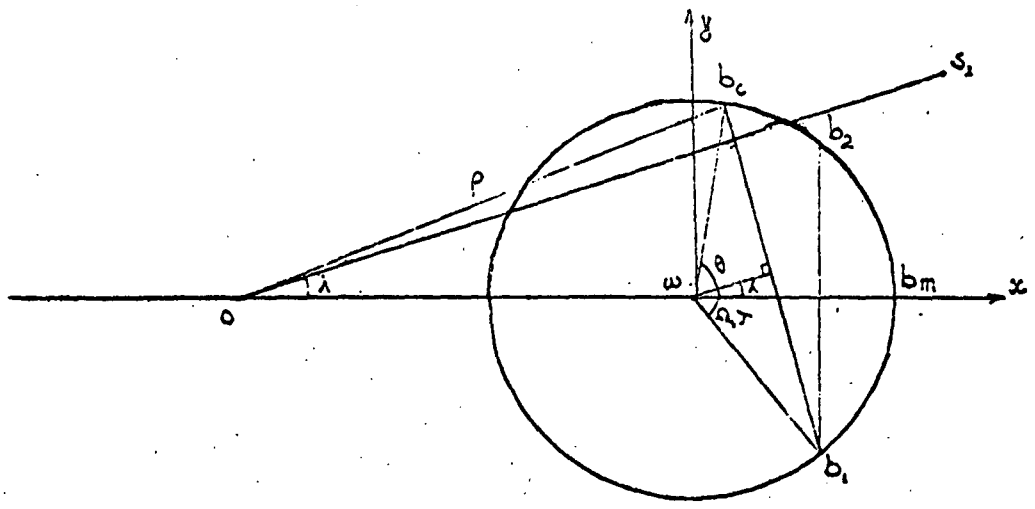


Fig. 6 .

Since the position of S_1 is determined by λ let us express $\widehat{b_1 \omega b_c}$ as

$$\widehat{b_1 \omega b_c} = 2(\lambda + \Omega_s T) = \theta + \Omega_s T$$

from which

$$\theta = 2\lambda + \Omega_s T$$

Let us determine the altitude z of B_C ($z = b_c B_C$). By stating

$$0 b_c = \rho$$
$$0 \omega = \omega$$
$$\omega b_c = r$$

$$\rho^2 = \omega^2 + r^2 + 2\omega r \cos\theta$$

from which (sphere of balloons of radius 1)

$$z^2 = 1 - \rho^2$$

$$B_m \begin{vmatrix} r \\ 0 \\ \sin\varphi \end{vmatrix} \qquad B_c \begin{vmatrix} r\cos\theta \\ r\sin\theta \\ z \end{vmatrix}$$

Consequently

$$Q^2 = B_M B_c^2 = r^2 (\cos^2\theta - 1)^2 + r^2\sin^2\theta + (z-\sin\varphi)^2$$

and

$$Q Q'' = r^2 \sin\theta + z' (z - \sin\varphi)$$

and also

$$2 z z' = 2 \omega r \sin\theta$$

QQ^1 then is explained in the form

$$QQ'' = \sin\theta \left[r^2 + \frac{\omega r}{z} (z-\sin\varphi) \right] = 0$$

for the extrema. First solution:

$$\theta = 0 \qquad \lambda = - \frac{\Omega_s T}{2}$$ symmetrical bases.

Second solution:

$$r^2 \frac{\omega r}{z} (z-\sin\varphi) = 0 \qquad z(r+\omega) = \omega \sin\varphi$$

or, by utilizing $z^2 = 1 - \rho^2$,

$$2\,\omega\, r \cos\theta = 1-\omega^2-r^2 - \frac{\omega^2 \sin^2\varphi}{(\omega + r)^2}$$

$$\cos\theta = \frac{1}{2\omega r}\left[\, 1-\omega^2-r^2 - \frac{\omega^2 \sin^2\varphi}{(\omega + r)^2}\right]$$

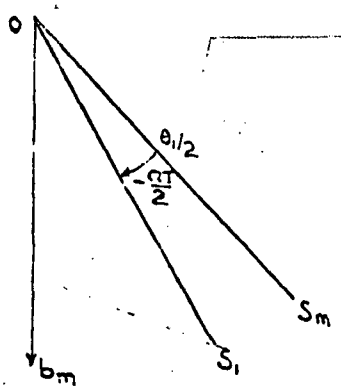
with $\omega = 0$ $\omega = \cos\varphi \cos\alpha - r \cos \Omega_s T$

$$r = \frac{\cos\varphi \sin\alpha}{\sin \Omega_s T}$$

from which $\theta = \theta_1$ et $\theta = -\theta_1$

and $\lambda = \frac{\theta_1}{2} - \Omega_s T/2$ $\lambda = -\frac{\theta_1}{2} - \frac{\Omega_s T}{2}$

which corresponds for S_m to two symmetrical positions of polar angle $-\theta_1/2$, $+\theta_1/2$, in relation to the mean balloon



Let us note that the angle $\theta/_2$ is equal to that of the orbital meridian planes of B_m and of S_M. The preceding formula can be written as

$$\cos\theta = \cos\Omega_s T + \frac{\sin^2\varphi}{2}\left[\frac{1}{\omega(\omega+r)} + \frac{1}{(\omega + r)^2}\right]$$

where W = speed of wind.

If T is small, we have, by considering the developments limited, if

$$\alpha = \frac{WT}{2\cos\varphi}$$

$$r \simeq \frac{W}{2\Omega_s}\left[1 + \frac{\Omega_s^2 T^2}{6}\right]$$

$$\omega \sim \cos\varphi + \frac{W}{2\Omega_s}\left[-1 + \frac{\Omega_s^2 T^2}{3} + \frac{W T^2 \Omega_s}{2\cos\varphi}\right]$$

with $\frac{W}{2\cos\varphi} \ll \Omega_s$

Consequently:

- for small distances in relation to the trace $\sin^2 \phi$ very small and $\cos\theta \simeq \cos \Omega_s T$
- with ϕ established and when T increases, ω v and r increase which causes the decrease of the expression

$$\left[\frac{1}{\omega\ (\omega+r)} + \frac{1}{(\omega + r)^2}\right]$$

We thus see that then $\cos\theta \simeq \cos\Omega_s T$

We can therefore conclude that, for short distances from the trace and the largest T among those considered, we shall have approximately $\theta = \Omega_s T$, which corresponds to B_c at B_1 or B_2 with

$$Q = B_M B_1 = B_M B_2 \quad \frac{WT}{2}$$

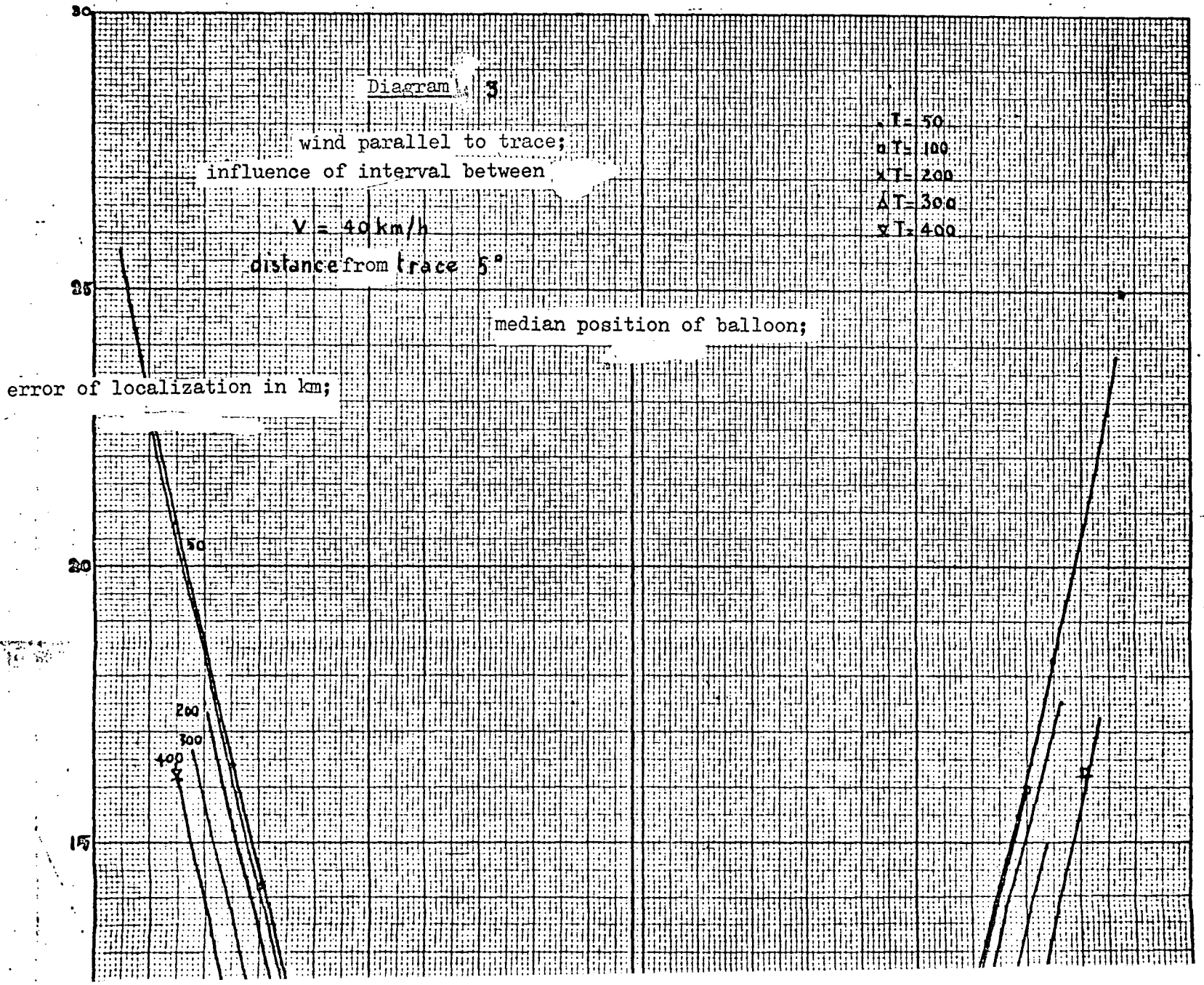


Diagram 3
wind parallel to trace;
influence of interval between
V = 40 km/h
distance from trace 5°
median position of balloon;
error of localization in km;
ΔT= 50
□T= 100
×T= 200
ΔT= 300
⧖T= 400
30
25
20
15
50
200
300
400

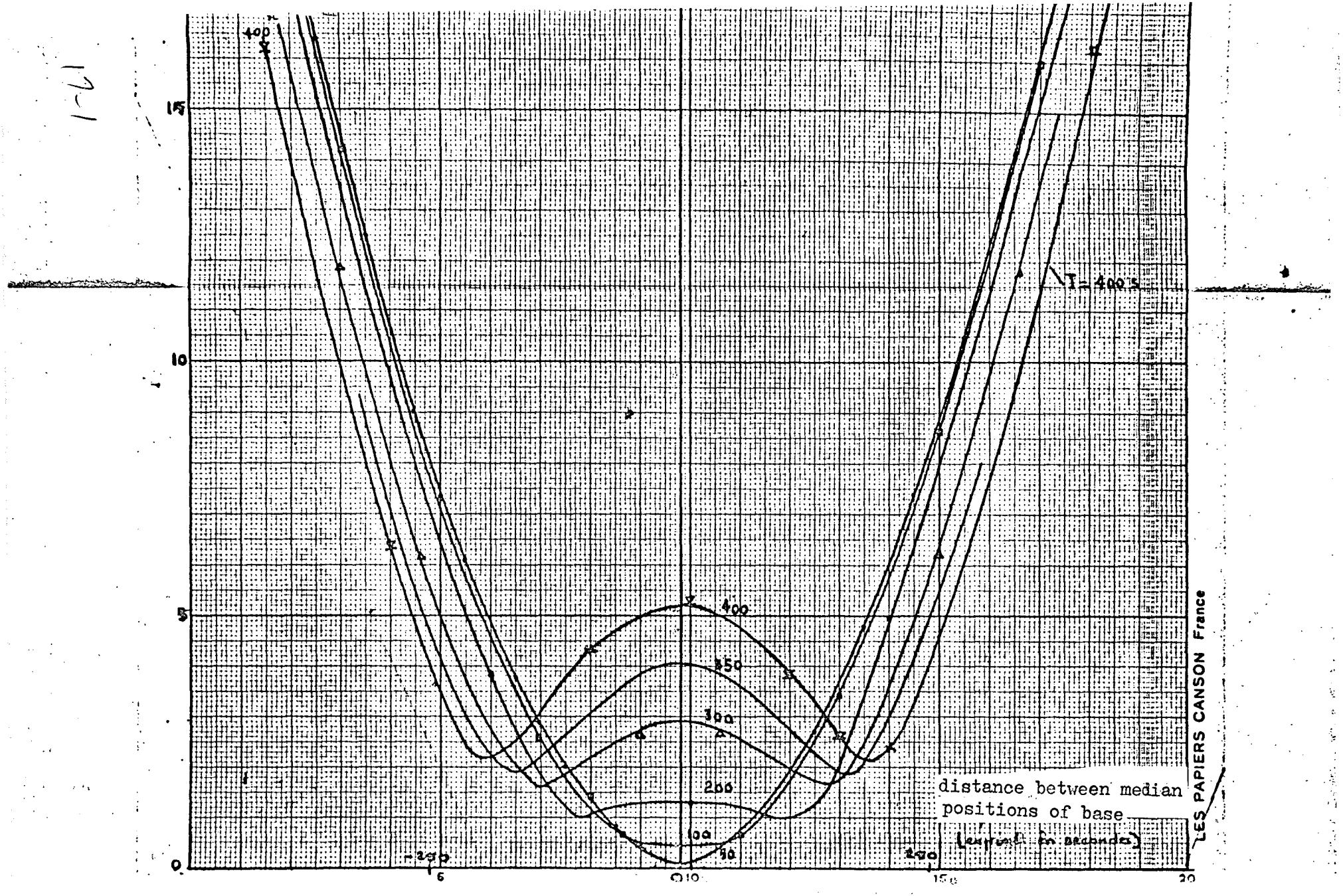

400
350
300
200
100
50
T = 400 s
distance between median positions of base
(expressed in seconds)
LES PAPIERS CANSON France
0
5
10
15
20

Diagram 4

wind parallel to trace;

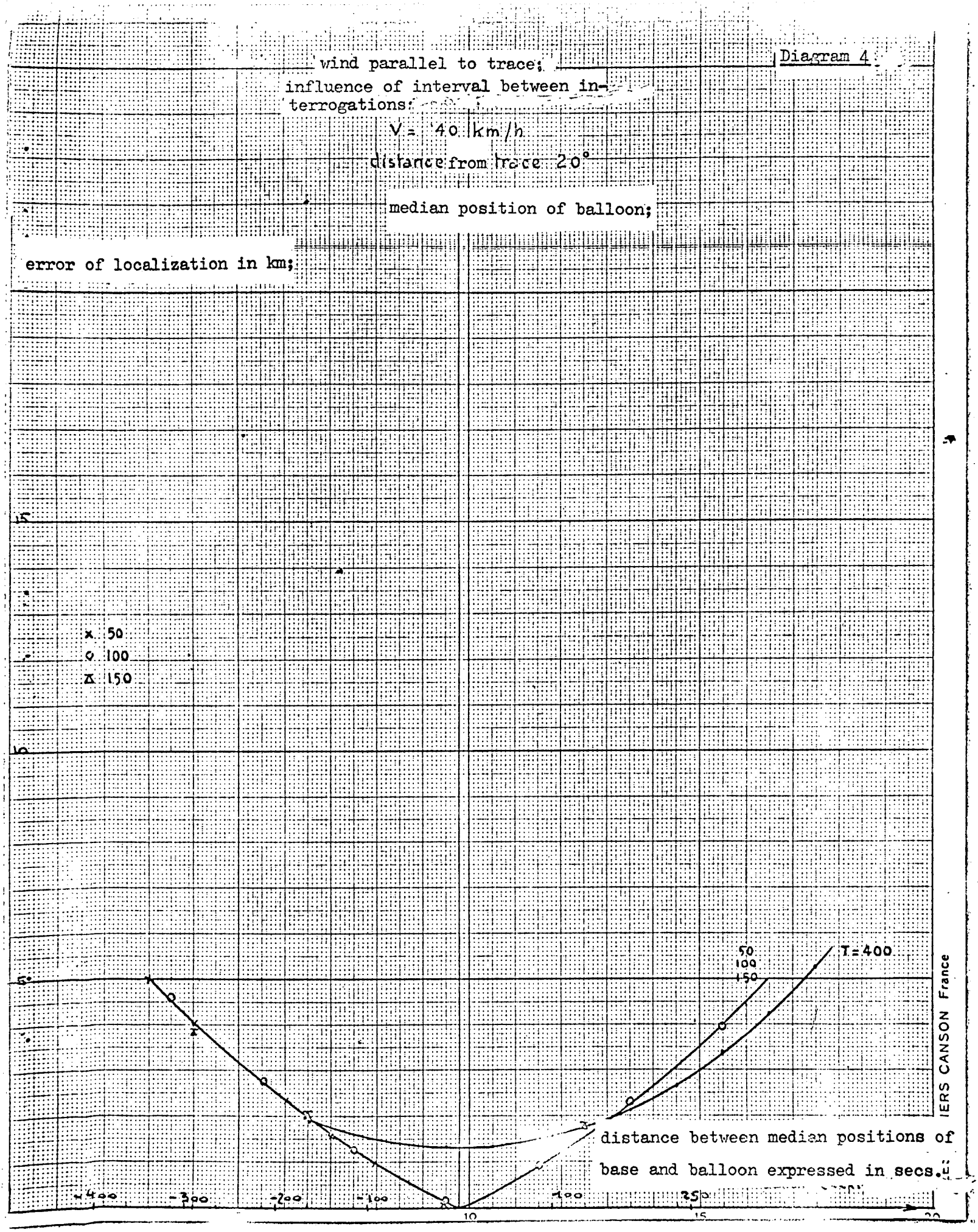
influence of interval between interrogations;

V = 40 km/h

distance from trace 20°

median position of balloon;

error of localization in km;



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as minimum error. We shall verify this statement on the subsequent diagrams.

2.1.2 -- Influence of the interval between interrogation :

When the interval between interrogation increases, the displacement of the balloon between the two instants of interrogation (B_1 and B_2) also increases for a given wind. We must therefore expect that the error of localization increases equally. In fact, we must also take into account the position of the bases.

On diagrams 3 and 4 have been traced the curves giving the overall error of location for a wind of 40 km/hr parallel to the trace for a balloon located at a distance from the trace of 5° and 20°.

We find that, for symmetrical bases, the error increases with the interval between interrogation, i.e. with the distance between the bases. We thus found, for a 40-km/hr wind and a satellite at 900 km, the following results for a balloon at 5° from the trace (cf. table)

Interval between interrogation T	50	100	200	300	350	400	en sec
Overall error in meters	105	500	1250	2900	4050	5200	m

The influence of the position of the bases in relation to the mean balloon is considerably as we saw in the preceding para. It should also be stressed that, when T increases, the symmetrical base may not be optimum (cf. diagram 2 as example). The symmetrical case then actually corresponds to a local extremum surrounded by two local minima which are produced approximately when S_1 is in the meridian of B_1 or S_2 in the meridian of B_2 and the value of these minima increases approximately linear with the interval between interrogation. Consequently, it will be advantageous to have:

a) long intervals of interrogation for very off-center bases (at the limit of visibility)

b) intervals of interrogation as low as possible for symmetrical bases

c) rather large T for median bases.

For "median" bases (centered half-way between the limits of visibility) we thus find the results of table 2 which can be compared to those indicated in table 1

Table 2.

T sec.	50	100	200	300	350	400
E m	7600		6800	5300	4400	3700

Depending on the position of the base, if we compare tables 1 and 2, we arrive at the inverse conclusions as plotted in fig. 7.

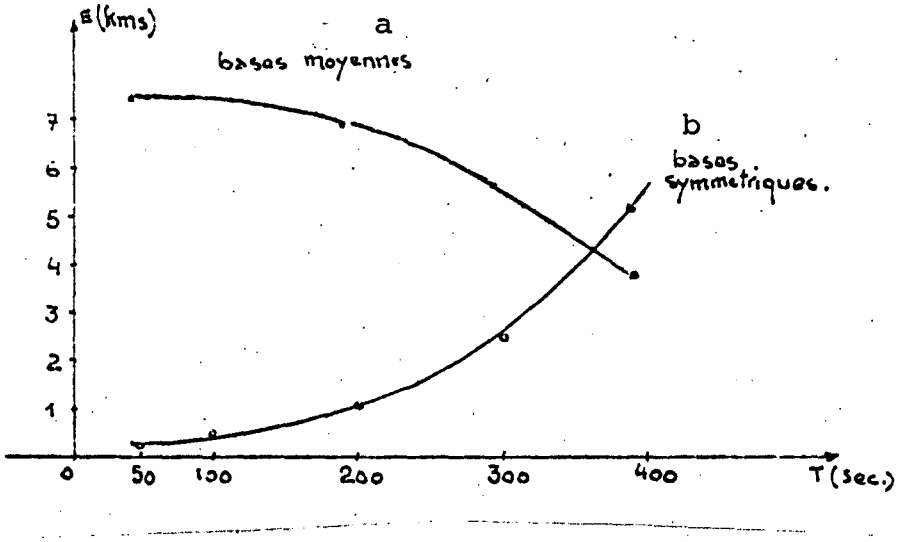


Fig. 7

a= median bases

b= symmetrical bases

This is due basically to the fact that, when T increases, the curve Q_2 slopes downward, i.e. the error of localization (of latitude for symmetrical bases) increases in absolute value and is negative.

LARGE DISTANCES FROM THE TRACE

The radius of the cylinder discussed in para. 2.1.1 is

$$r = \frac{\cos\varphi \sin\alpha}{\sin\Omega_s T} \quad \text{with } \alpha = \frac{w\,T}{2\cos\varphi}$$

For short T, we have $r \sim \frac{W}{2\Omega_s}$

where W = speed of wind. The position of the center is also given by $O\omega = \cos\varphi \cos\alpha - r.\cos\Omega_s T$

It is evident that these two magnitudes vary little for short T.

If we place ourselves at a slight distance from the trace, the slope of the plane tangent at B_M to the sphere of the balloons will have a high value and the slight variation of r and ω will produce appreciable variations for Q. This no longer holds true for large distances from the trace where we must expect that the influence of T will be negligible (diagram 4).

2.1.3 - Influence of distance from the trace:

In general, the error of localization increases when the balloon approaches the trace and this effect is as much more appreciable as the off-centering between median base and mean balloon itself is greater.

If we add to this phenomenon the fact that, when the balloon moves away from the trace, the zone of visibility and consequently the off-centering is reduced, the influence of distance from the trace becomes extremely important in an overall manner.

F Diagram 5

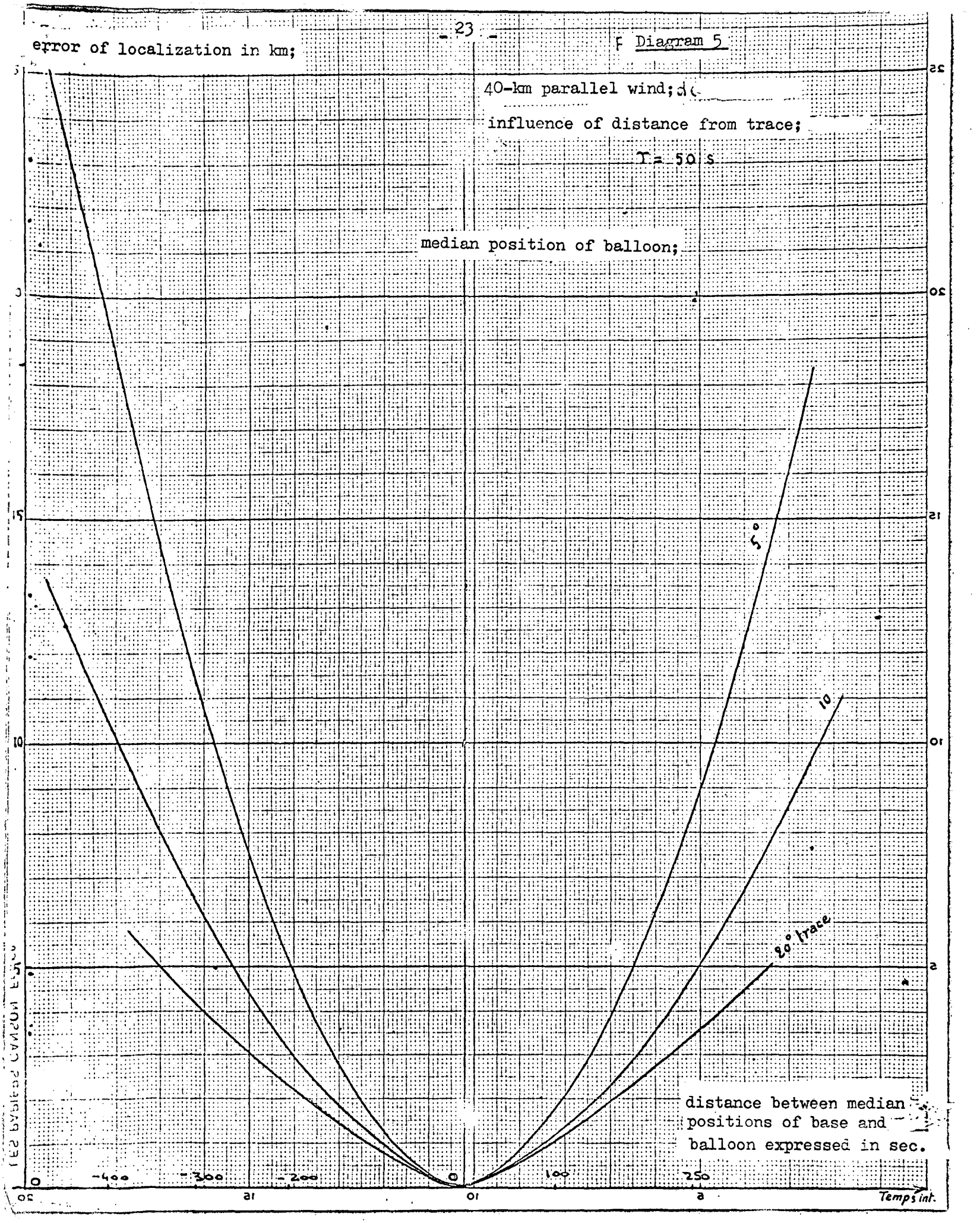

error of localization in km;
40-km parallel wind;
influence of distance from trace;
T = 50 s
median position of balloon;
5°
10
20° trace
distance between median positions of base and balloon expressed in sec.
-400
-300
-200
100
250
Temps int.

Diagram 6

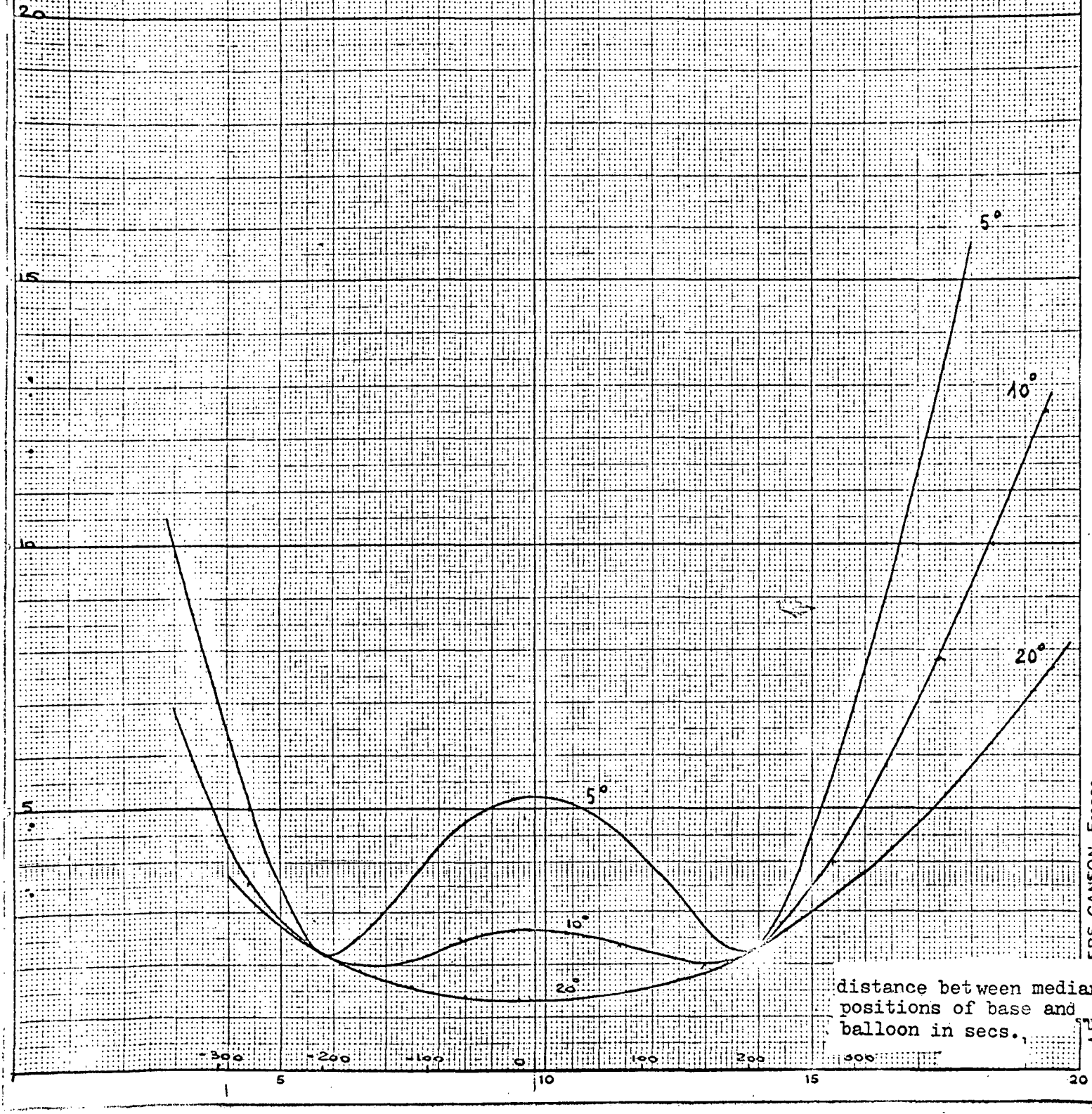
influence of distance from trace;

40-km parallel wind;

T = 400 s

error of localization in km;

mean position of balloon



ERS CANSON France

When the first base is at the limit of visibility, we thus found the following errors of location expressed in meters:

	5°	10°	20°	
First base	25.500	12 600	5 000	T = 50 sec
	6.400	3.500	1 900	T = 400 sec

For symmetrical bases, the results are the following:

	5°	10°	20°	
Symmetrical bases	80	40	20	T = 50 sec
	5250	2620	1530	T = 400 sec

Diagram 6 makes it possible to verify that the symmetrical minima vanish when ϕ increases. This condition corresponds to the existence of θ as indicated in para. 2.1.1.

On the other hand, since T is established, the distance $B_M B_1$ and $B_M B_2$ are known, for a given wind strength, independent of the distance from the trace. Consequently, for the median position of the satellite corresponding to $\theta/2 = \frac{\Omega_s}{2} T$, B_c appears at B_1 with an error $Q = B_M B_1$ independent of ϕ. Similarly, for $\theta/2 = -\Omega_s T/2$, B_c appears at B_2. So that we obtain the two points common to all curves with reduced abscissae $\pm T/2$ and with ordinate $Q = w\ T/2$

($w - v_R$ = speed of wind).

2.1.4 - Influence of wind strength:

The error of localization obviously increases with wind strength and is moreover proportional to it (cf. diagrams 7 and 8) at least then when the angle α is sufficiently small so that we can assimilate the sine and the angle.

2. 1. 5 - Influence of wind direction:

We have also considered the influence of wind direction. In the preceding paras., it was assumed that the direction of the wind and the displacement of the satellite were the same. This was recalculated by considering the opposite case. The equations of para. 2.1.1. show that the problem is not changed since B_M and the cylinder under consideration are the same. Reference should be made to diagram 9 which can be compared to diagram 3.

2.2 WIND PERPENDICULAR TO THE TRACE

Here we utilize the formulas proposed in para. 1.2 which will furnish the computation program given in the Annex with the error of "latitude" Q_2; error of "longitude" Q_3; and overall error Q_4. The positive direction of the wind was selected as that moving

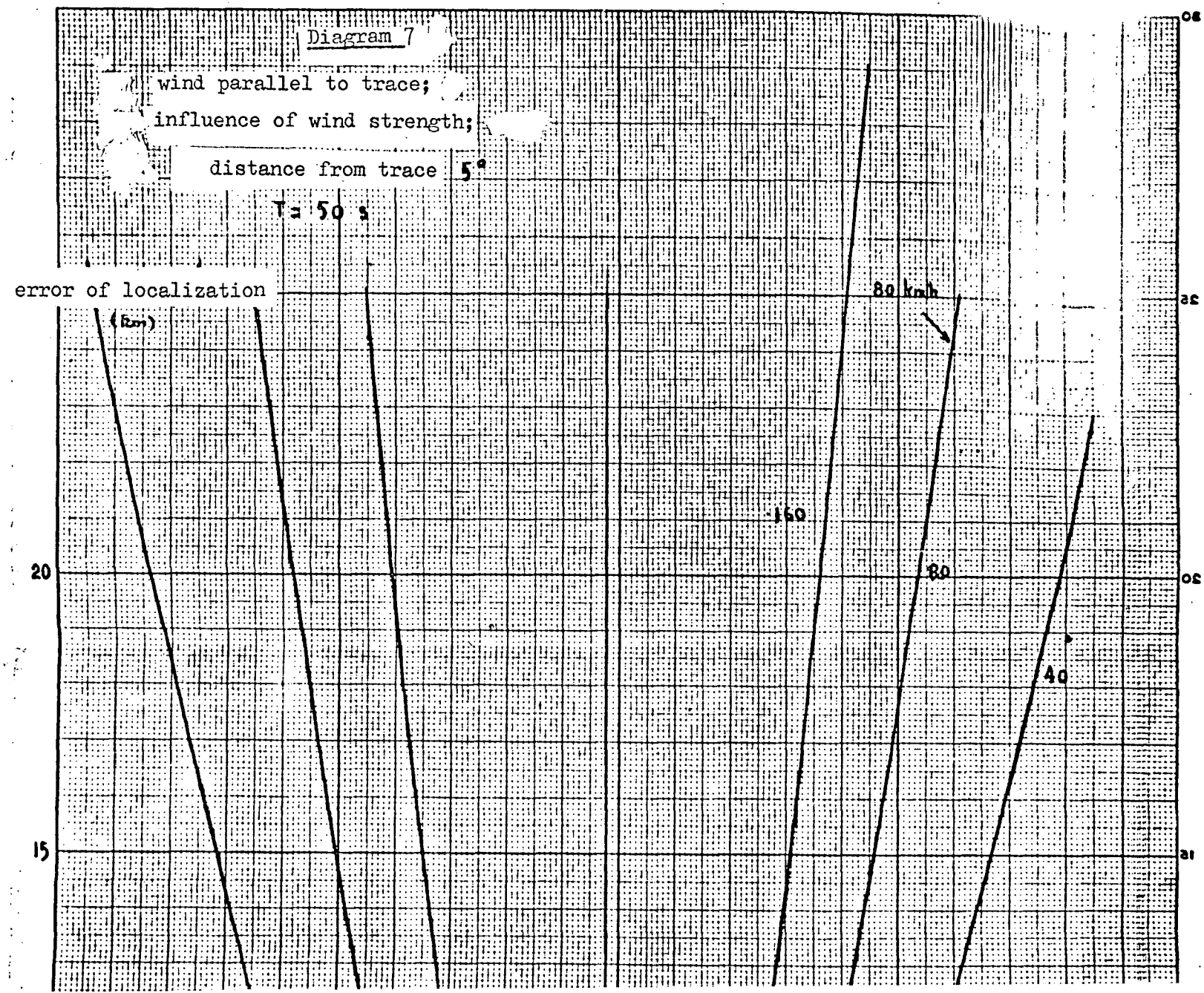


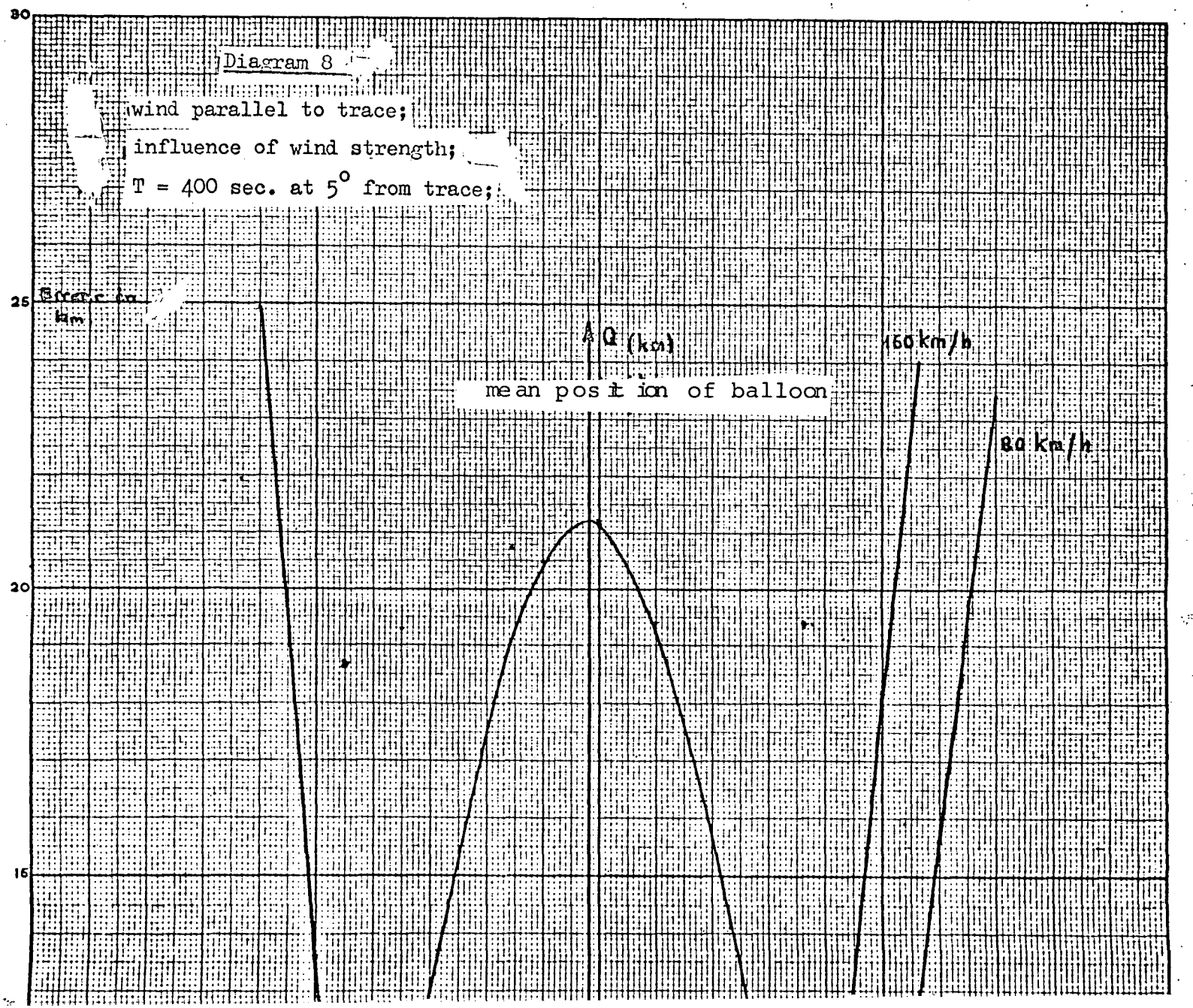
Diagram 7
wind parallel to trace;
influence of wind strength;
distance from trace 5°
T = 50 s
error of localization
(km)
80 km/h
160
80
40
20
15

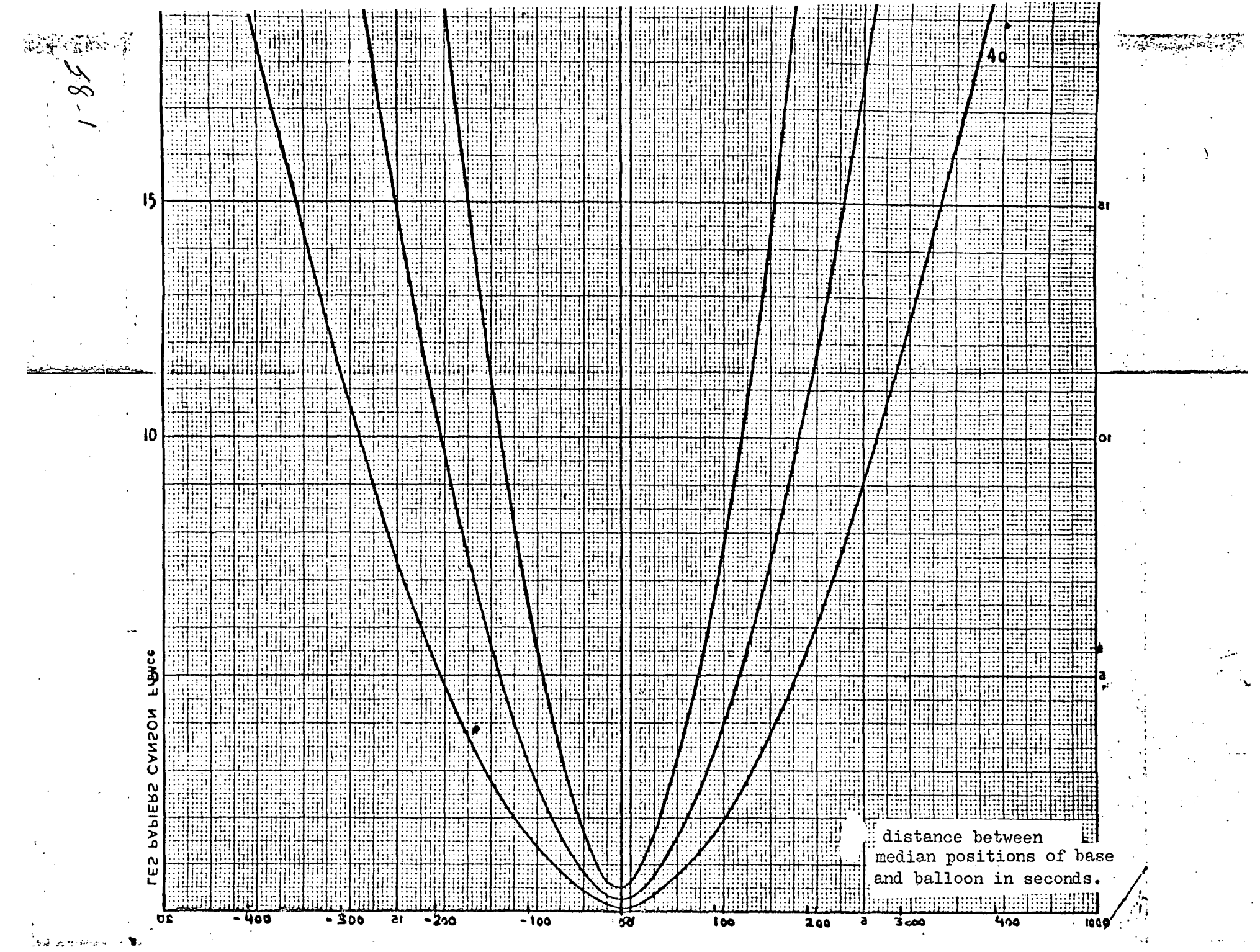
Diagram 8

wind parallel to trace;

influence of wind strength;

T = 400 sec. at 5° from trace;




98-1
40
15
10
distance between
median positions of base
and balloon in seconds.

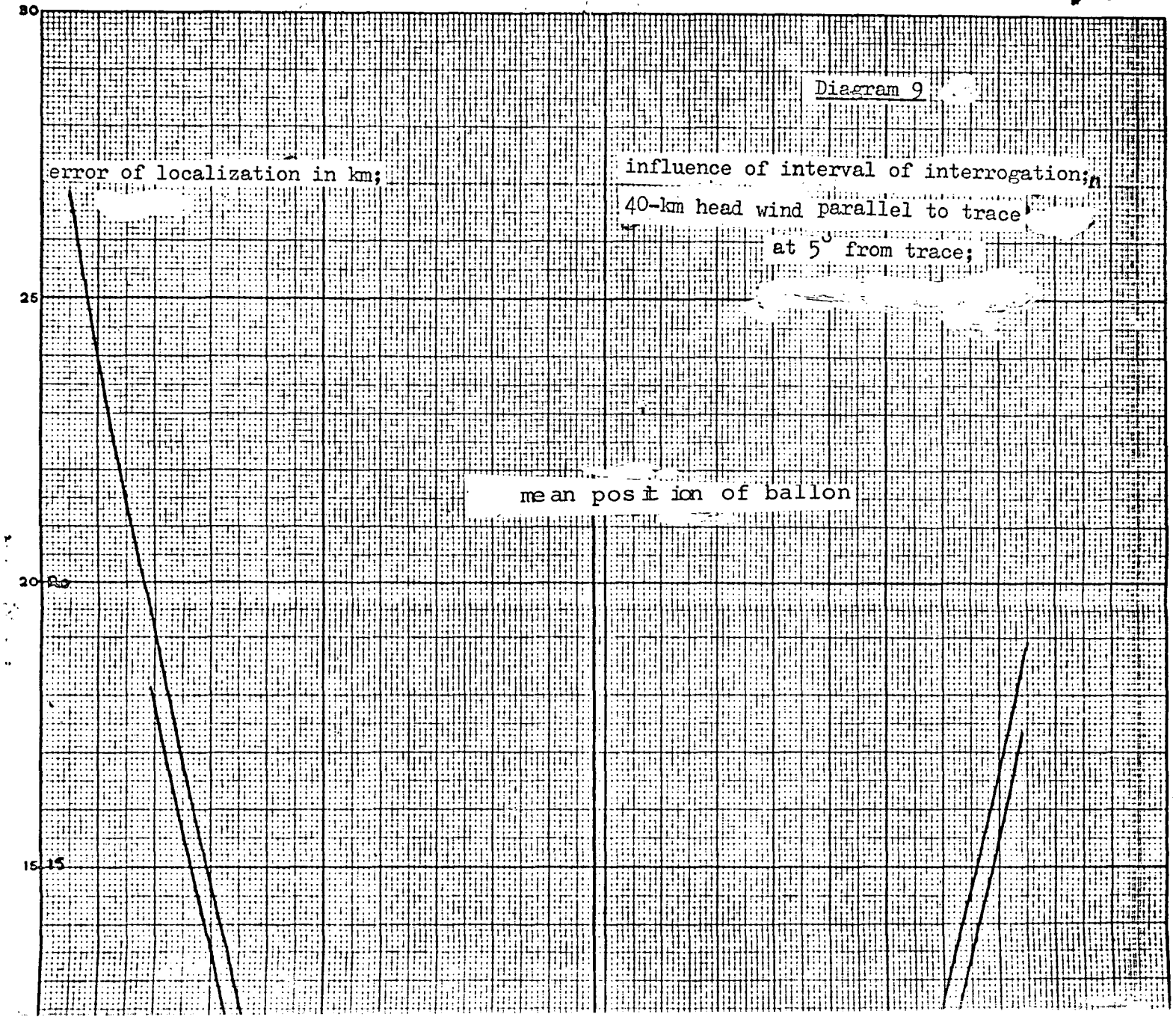
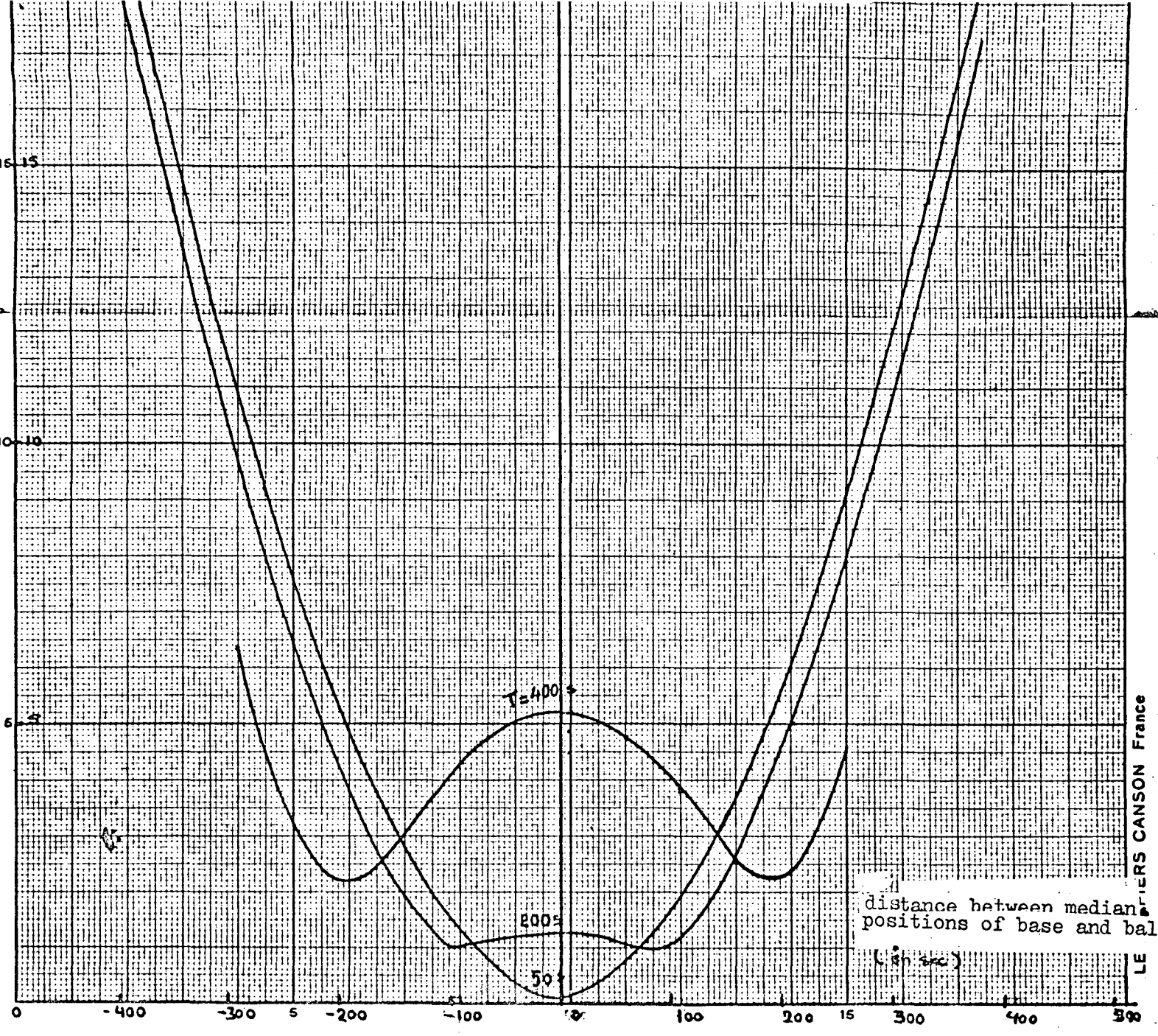
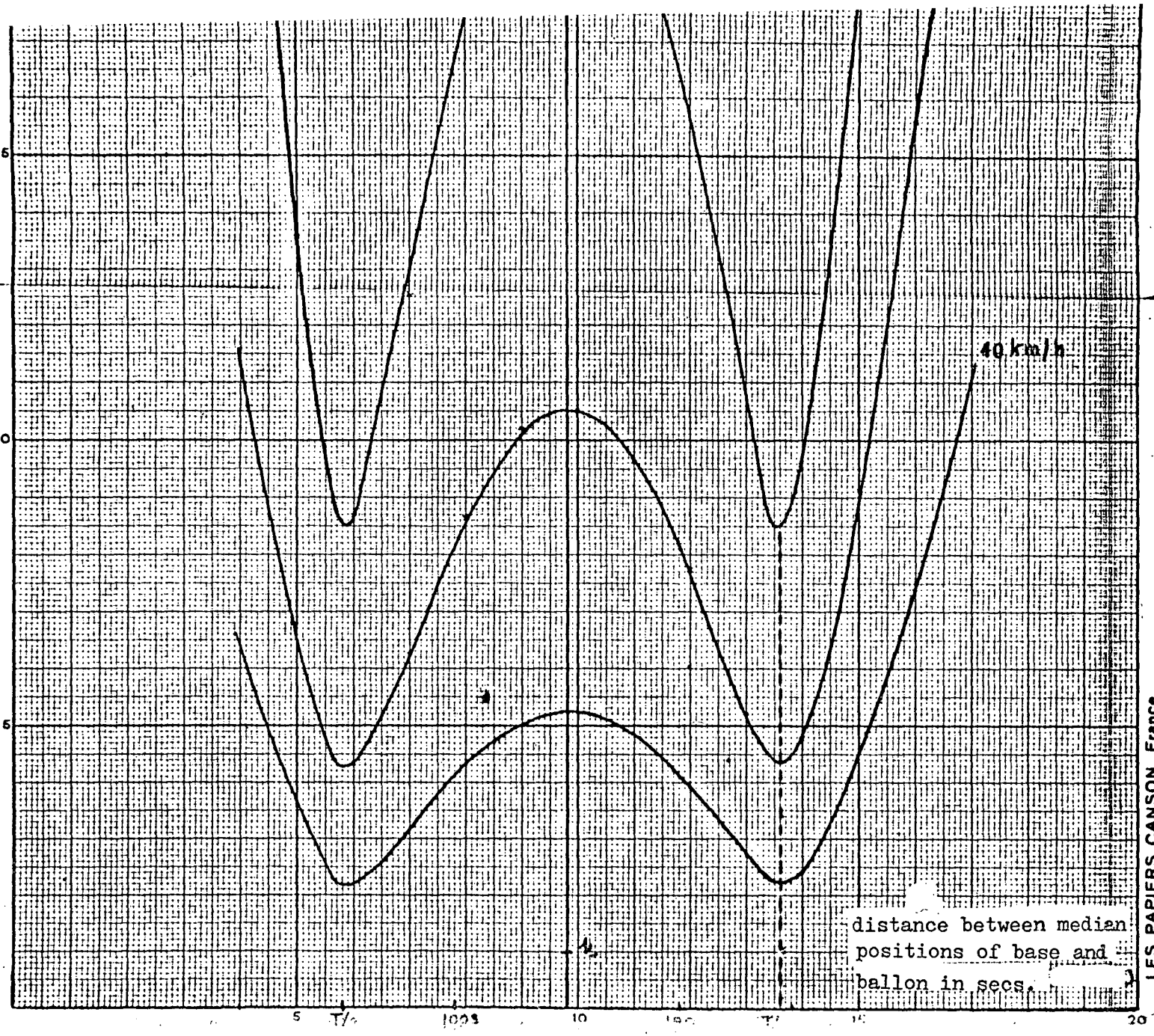


Diagram 9
error of localization in km;
influence of interval of interrogation;n
40-km head wind parallel to trace
at 5° from trace;
mean position of ballon
30
25
20
15


15
10
6
T=400 s
200 s
50 s
0
-400
-300
-200
-100
100
200
300
400
distance between median positions of base and balloon
(in sec)
CANSON France

29-1


15
10
5
40 km/h
distance between median positions of base and ballon in secs.
5
10
20
LES PAPIERS CANSON France

29.2

the ballons away from the trace.

2.2.1 - Influence of base positions (diagram 10)

By using the same definition for the error $Q = B_M B_C$ for wind parallel to the trace, we obtain the form of the curve plotted in diagram 10. We find a minimum for the symmetrical bases with cancellation of the error of latitude Q_2. Comparison with diagram 1 discloses an error appreciably less at the limit of visibility (5 instead of 25 km). The conclusions are reversed for centered bases (with an error) of 1 km for wind perpendicular to the trace and about 100 m for wind parallel to the trace.

Let us justify the form of these curves as in para. 2.1.1. On fig. 8-a plotted in the plane of the orbit, we recognize in the circle ($\omega, \omega b_1$) i.e. locus of b_c, b_1, b_2, b_m, , the projections of B_1, B_2, B_M. We have: the angle

$$b_c \widehat{\omega} b_1 \qquad = (\theta - \Omega_s T \;) \; = 2\left(\pi/2 - \lambda - \Omega_s T\right)$$

from which

$$\theta = \pi - \Omega_s T - 2\lambda$$

On the other hand, in fig. 8-b

$$Ob_1 = \cos(\varphi - \beta) \qquad Ob_2 = \cos(\varphi + \beta)$$

and if b_o is the midpoint of $b_1 b_2$: $b_o b_1 = \sin\varphi \sin\beta$

We also have

$$ob_m = \cos\varphi$$

$$ob_0 = ob_1 + \frac{b_1 b_2}{2} = \cos\varphi\cos\beta$$

d'où

$$b_0 b_m = 2\cos\varphi \sin^2 \beta/2$$

Returning to fig. 8-a

$$r = \omega b_1 = \frac{b_0 b_1}{\sin \Omega_s T} = \frac{\sin\varphi \sin\beta}{\sin \Omega_s T}$$

We deduce from this that, if T, w/Ω_s are small,

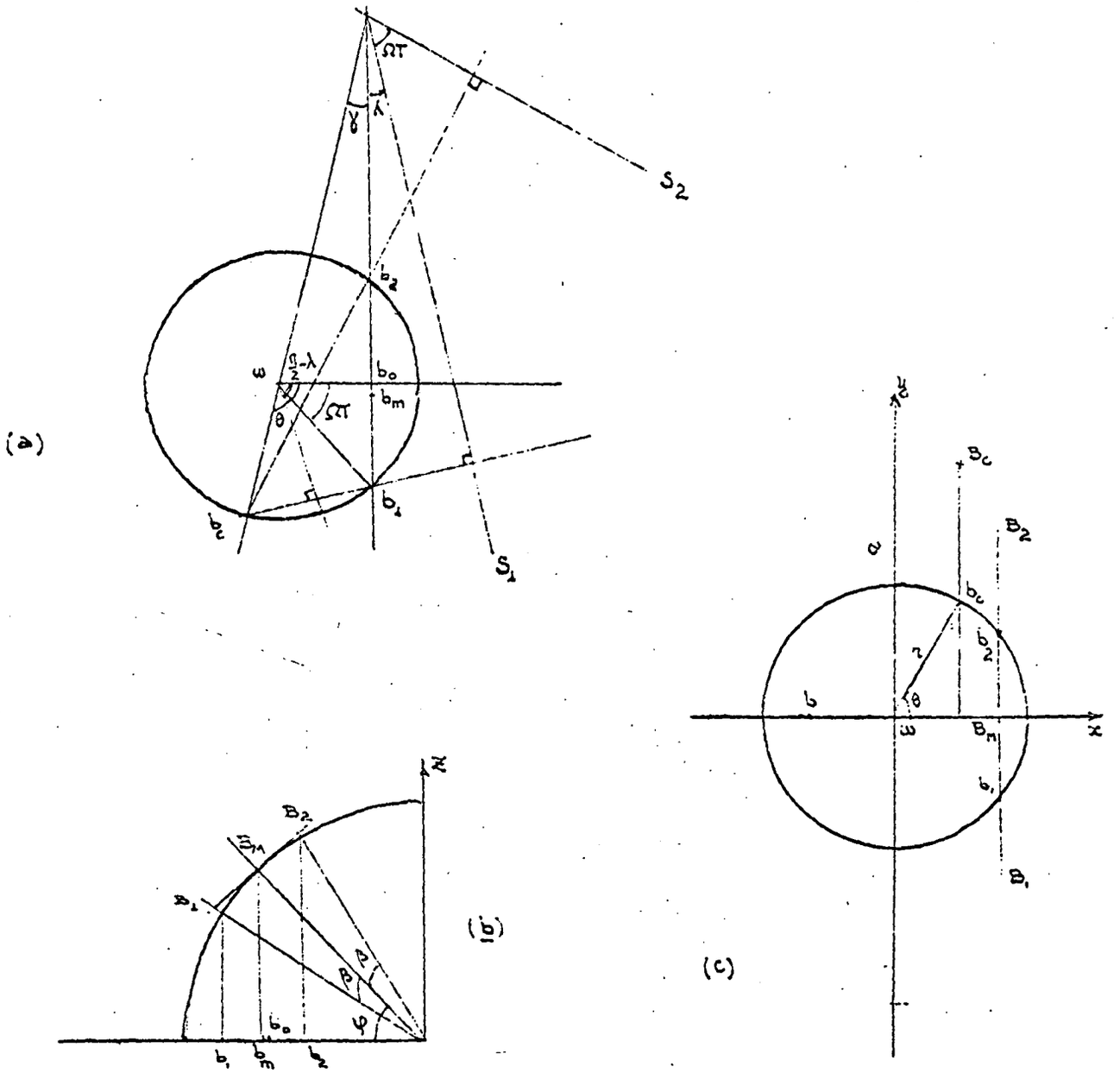
where $\quad "a" = \dfrac{r}{\sin\varphi} \quad$ et $\quad "b" = r$

Since the radius of the cylinder is small, we subsequently merge the sphere with its plane tangent at B_M. B_c is therefore found approximately on the ellipse shown in fig. 8-c where "a" = r/sin ϕ and "b" = r. In the axes indicated in this tangential plante:

$$B_b \left| \begin{array}{l} x = r\cos\theta \\ y = \dfrac{r}{\sin\varphi}\sin\theta \end{array} \right. \qquad B_M \left| \begin{array}{l} r\cos \Omega_s T \\ 0 \end{array} \right.$$

The extrema (?) of Q are obtained for the normals to B_c passing through B_M;

from which $\quad B'_c \left| \begin{array}{l} x' = -r\sin\theta \\ y' = \dfrac{r\cos\theta}{\sin\varphi} \end{array} \right.$ $\quad$ and $\quad B_M B_c \left| \begin{array}{l} r(\cos\theta - \cos\Omega_s T) \\ r\dfrac{\sin\theta}{\sin\varphi} \end{array} \right.$


(a)
S_2
S_1
ΩT
γ
$\frac{\gamma}{2}$
θ
b_0
b_m
b_1
b_2
(b)
B_2
B_1
Φ
(c)
B_0
B_2
B_1
B_E
r
θ

Figures 8

Diagram 10

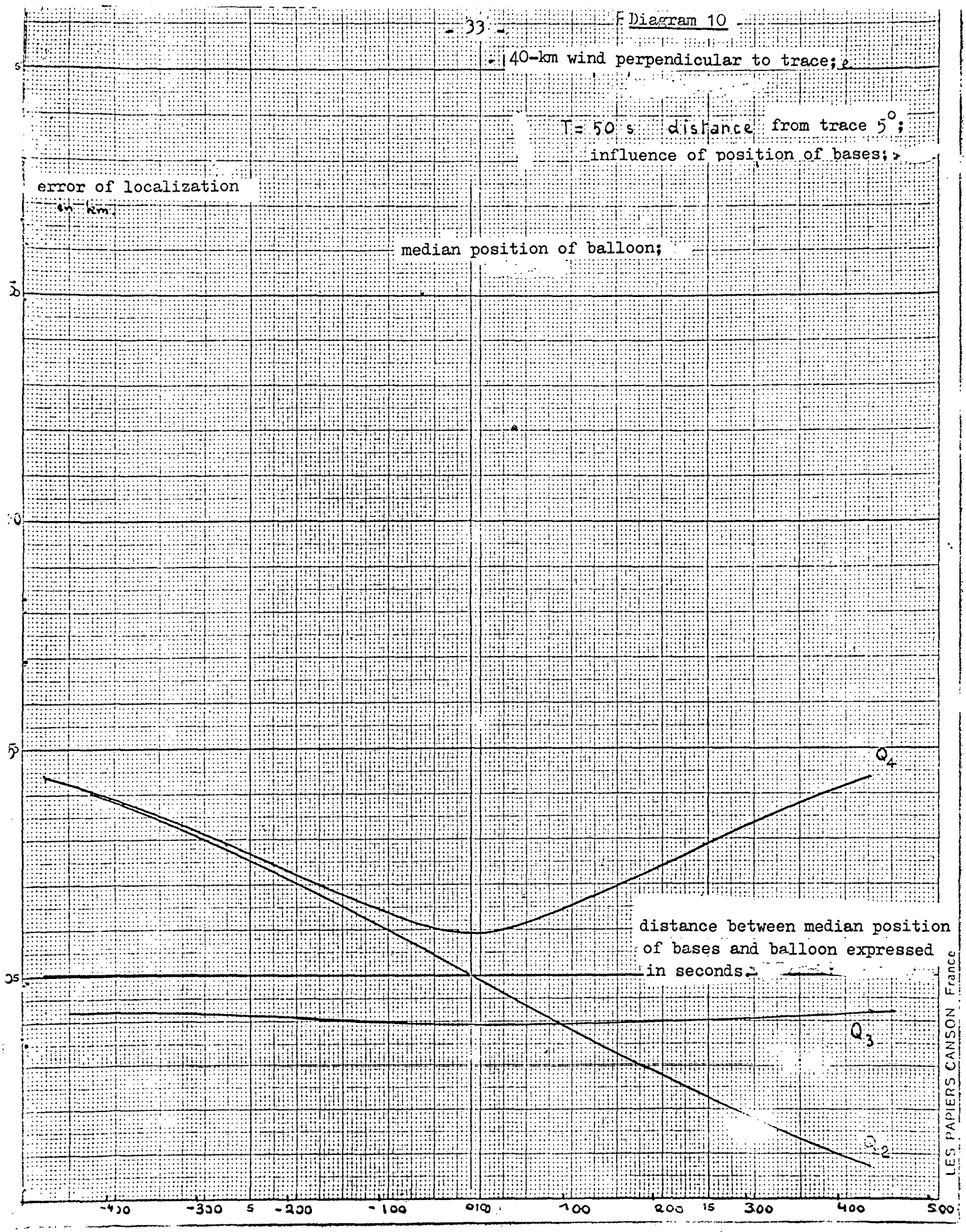
40-km wind perpendicular to trace;

T = 50 s distance from trace 5°;

influence of position of bases;

error of localization in km;

median position of balloon;



The condition therefore is:

$$- r^2 \sin\theta (\cos\theta - \cos\Omega_s T) + r^2 \frac{\sin\theta \cos\theta}{\sin^2\varphi} = 0$$

from which $\sin\theta = 0$ $\theta = 0$

$\theta = \pi$

$$\boxed{\lambda = -\frac{\Omega_s T}{2}}$$ symmetrical bases

and $\cos\theta = -\cos\Omega_s T \; tg^2\varphi$

with solutions of the form $\theta = \pi - \theta_1$ $\theta = \pi + \theta_1$ $\boxed{\lambda = \pm\frac{\theta_1}{2} - \frac{\Omega_s T}{2}}$

or two positons of S_M symmetrical in relation to the orbital meridian plante of B_M which are independent of the wind strength.

2.2.2 - Influence of distance from the trace :

The results obtained for T = 50 sec and different distances

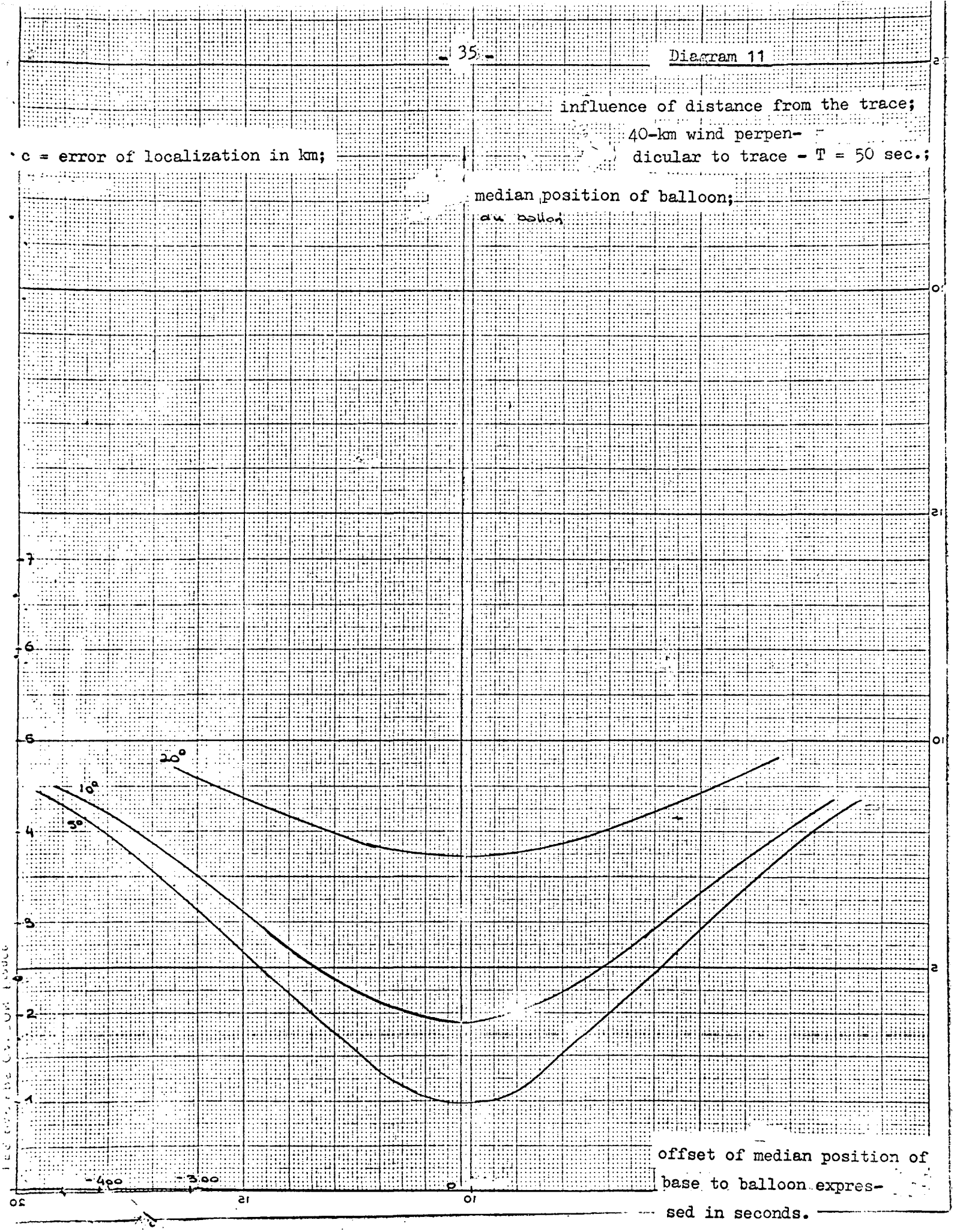
Diagram 11

influence of distance from the trace;

40-km wind perpendicular to trace - T = 50 sec.;

c = error of localization in km;

median position of balloon;



offset of median position of base to balloon expressed in seconds.

from the trace are plotted in diagram 11. We find that the curves become concave at the emplacement of the centered bases when the distance from the trace diminishes and that, in general, large ϕ gives the largest errors. These results can be explained by turning to the considerations of para. 2.2.1. This is due to the fact that, when the distance from the trace ϕ increases, the form of the ellipse, i.e. locus of B_c, approaches that of the circle. The variations of Q will therefore be of lesser amplitude.

On the other hand, we saw that symmetrical bases corresponded to $\Theta = \pi$ with a consequent error $Q_m = r + r \cos \Omega_s T$ or $Q_m = r\,(1+\cos \Omega_s T) = \dfrac{\sin\varphi \sin\beta}{\sin \frac{\Omega_s T}{2}}$

We clearly find that Q_m increases with ϕ .

2.2.3 - Influence of interval between interrogation:

Let us consider the expressions calculated for b_o ω and r where we have

$$r = \frac{\sin\varphi \sin\beta}{\sin \Omega_s T} \quad \text{and} \quad b_o \omega = \frac{\sin\varphi \sin\beta}{\sin \Omega_s T}$$

with $\beta = \dfrac{w\,T}{2}$ w speed of wind $= v_\perp$

On the assumption of an interval T sufficiently small, we therefore have an approximate position of ω (through $b_o\omega$) and a radius independent of T. We must therefore expect a negligible influence of the interval between interrogation as we can verify on diagram 12 where the curves are superposed within the accuracy of the drawing.

2. 3 - INFLUENCE OF WIND DIRECTION

A very important point resulting from the preceding paras. is the following:

In the evaluation of the errors of localization, the direction of the wind is as important as its intensity. If we compare the results obtained in para. 2.1 and 2.2, we see that, at the same intensity, the errors for parallel wind are 5 times higher than for a perpendicular wind.

On the other hand, we find the influence of the distance from the trace was opposite in the two cases as shown by diagrams 11, 5, 6.

In both cases and particularly for short distances from the trace, it will be noted that the interval between interrogation has rather little effect (superposed curves of diagrams 4 & 12).

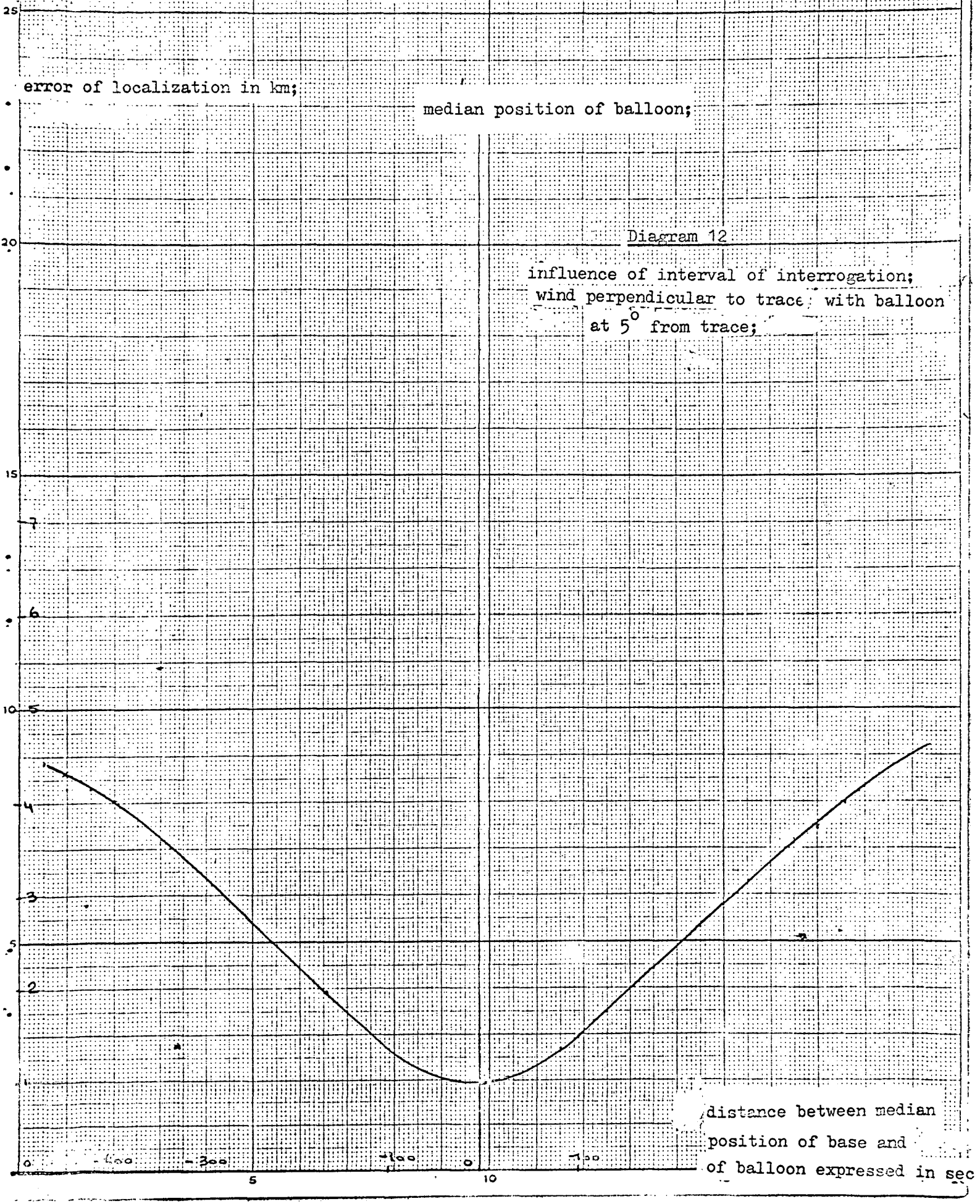
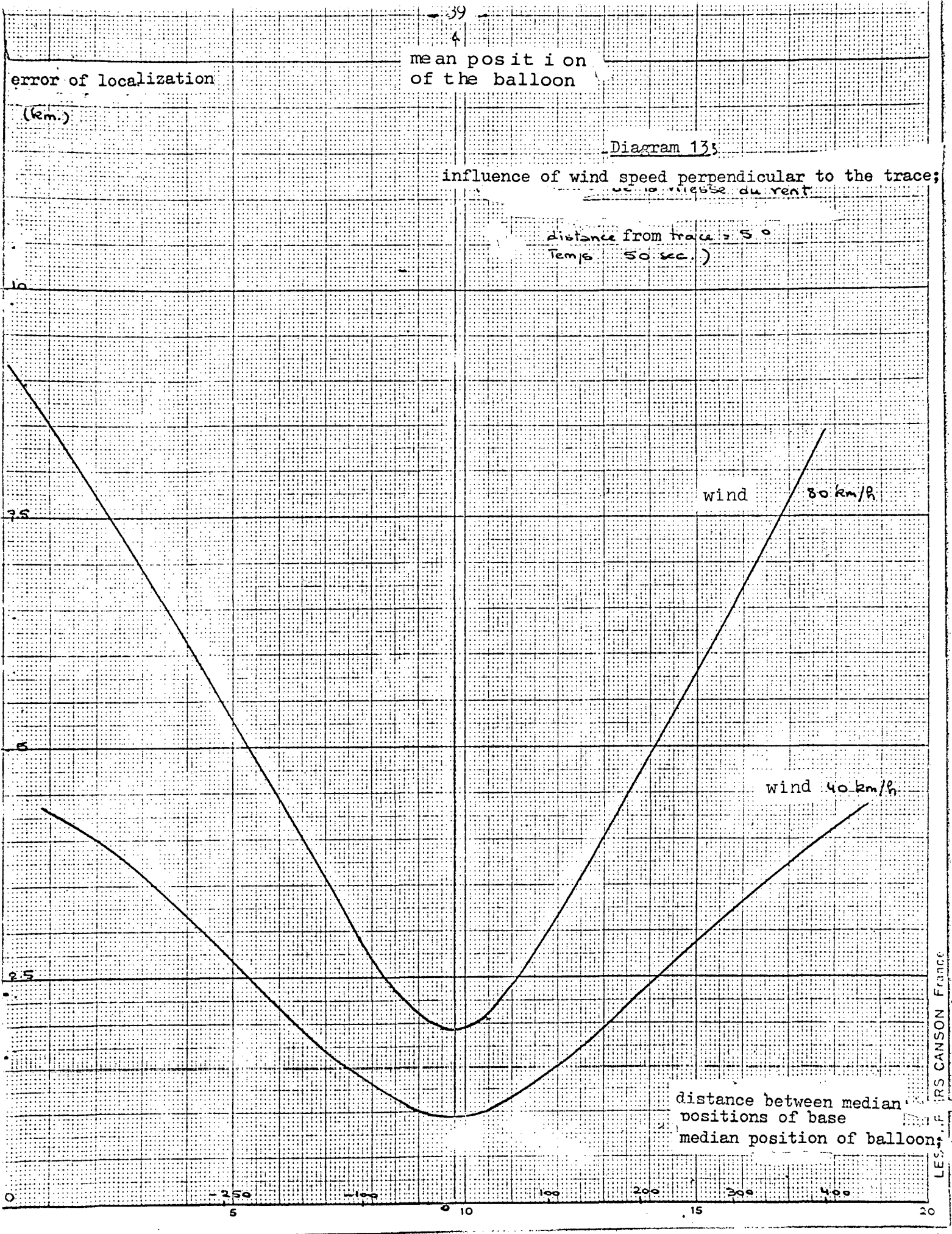


Diagram 12

influence of interval of interrogation;
wind perpendicular to trace with balloon
at 5° from trace;


mean position of the balloon
error of localization
(km.)
Diagram 135
influence of wind speed perpendicular to the trace;
distance from trace = 5 °
Temps 50 sec.)
10
7.5
5
2.5
0
wind 80 km/h
wind 40 km/h
distance between median positions of base
median position of balloon;
-250
-100
100
200
300
400
5
10
15
20

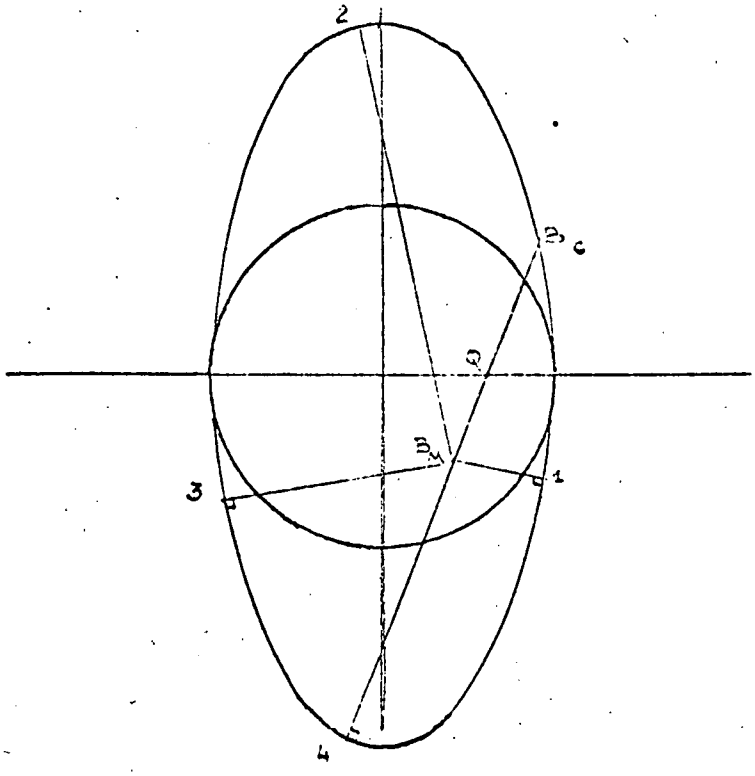


Fig. 9

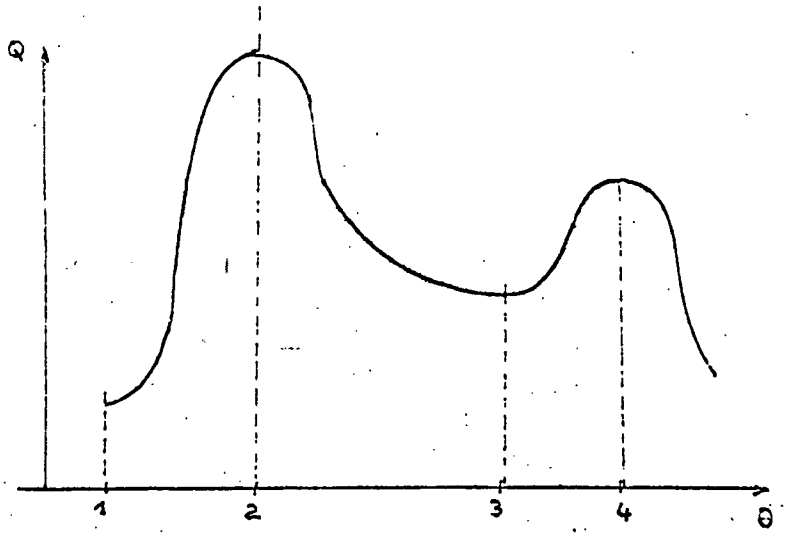


Fig.10

The theoretical study can be conducted in the same manner as in the preceding cases. We obtain for the locus of B_C an ellipse such as that shown in fig. 9 with B_M not located on an axis. For Q, we derive from this four extrema corresponding to the normals to the ellipse starting from B_M so that we can anticipate the form of the curves (cf. fig.10).

3. INDETERMINATE WIND

Let us consider an indeterminate wind with its parallel and perpendicular components known. Each of its components can be moreover divided into a continuous and an intermittend part. The necessity for dividing these componennts is due to the fact that, as we have shown in memorandum No 5 (Influence of terrestrial rotation), the errors due to continuous components can be corrected by an iterative process.

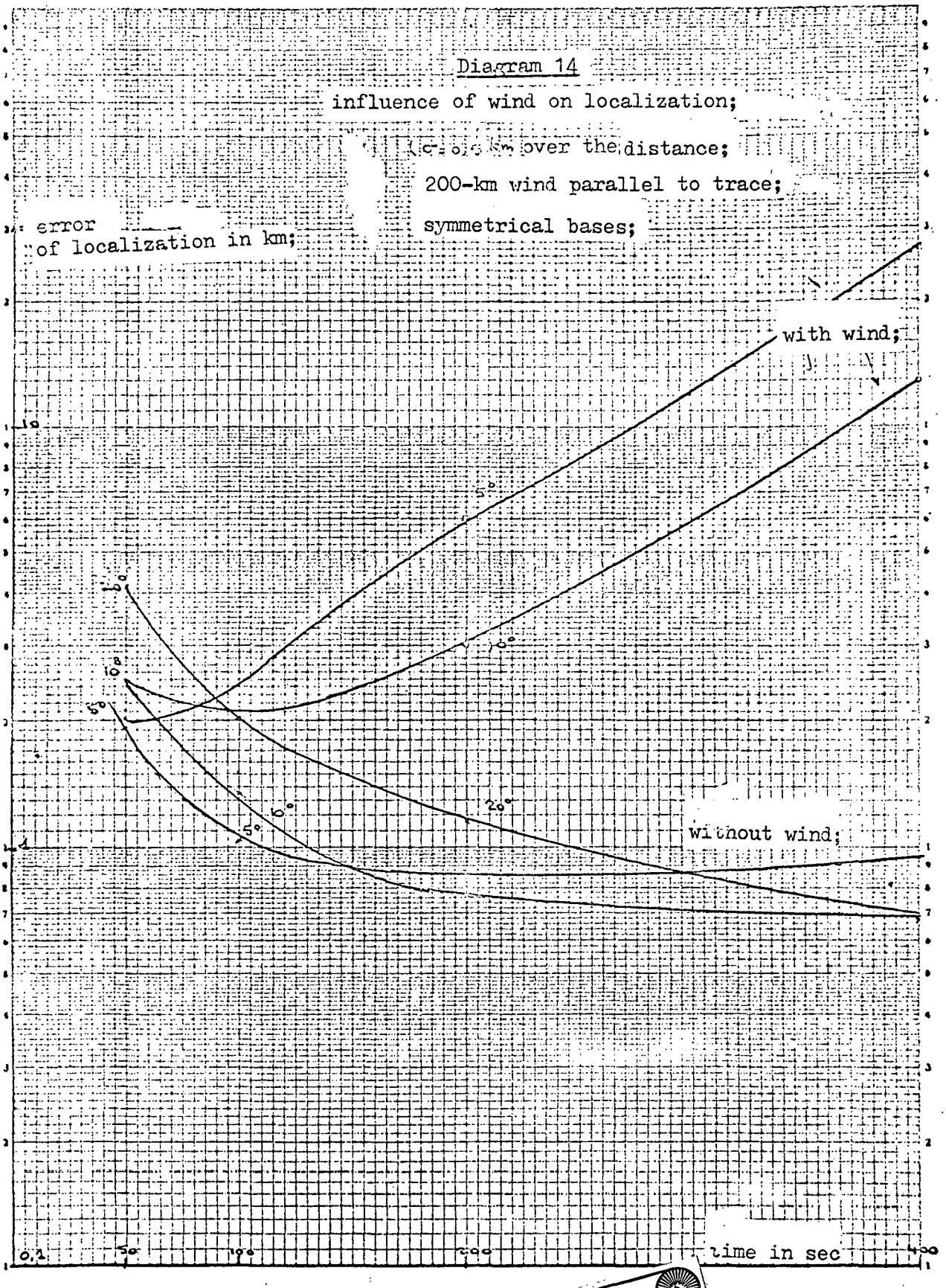
A first estimate of the influence of the wind on the errors of localization was made for the case where the measurements of distance are themselves affected by a measurement noise whose typical deviation was selected as equal to 500. In the Annex will be found the general computation program but, in view of the machine time required, the problem has been treated at this state only on the assumption of symmetrical bases and for a continuous wind of 200 km/hr parallel to the trace (the most unfavorable case).

The results of computation are embodied in table 3 where the results obtained without wind are also noted for comparison. This table brings us to diagram 14 where we plotted the mean error (estimated from 300 operations), rather than the probabilities of localization and where the scale utilized is logarithmic for greater clarity.

The following conclusions may be drawn from this diagram:

1. Whereas, if we take into account only errors of distance, it is generally advantageous to increase the interval between interrogation (in the case under consideration the orthonormal base is attained only for distances from the trace of 5°), the presence of a non-compensable wind component introduces errors of localization which increase very rapidly when the interval between interrogation increases. These errors may easily increase by a factor of 10 when T increases from 50 to 400 secs.

2. Without wind and for "short" rates, localization is better close to the trace (cf. Memorandum 6 on the influence of T).When the wind is taken into consideration, this leads to opposite conclusions and localization close to the trace is definitely less accurate since the error is practically doubled with median T when we are at 5°instead of 1°from the trace.



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Quadrillé Semi-Logarithmique à 3 modules

Table 3 - Localization of errors with wind and symmetrical bases

Orbit at 900 km; σ_d =0,5 km Wind of 200 km/hr

Symmetrical bases

distance from the trace 5°

Q Kms	T = 50 s.		T = 100 s.		T = 200 s.		T = 400 s.	
		Vent		Vent		Vent		Vent
1	76	79	138	19	174	0	170	0
2	97	90	134	159	122	0	118	
3	77	79	26	104	4	0	12	
4	27	28	2	17	0	0	0	
5	17	18	0	0		3		
6	5	4				80		
7	1	1				140		
8	0	0				70		
9						6		
10		0				0		0
> 10		0				0		300
Q mean	1,90	2	1,06	2	0,87	6	0,94	27

Distance from the trace 10°

Q	T= 50 s.		T= 100 s.		T= 200 s.		T= 400 s.	
1	83	89	120	114	206	0	245	0
2	84	46	120	116	89	0	55	
3	62	50	42	48	5	63		
4	39	60	16	17	0	217		
5	18	20	2	4		19		
6	15	17	0	0		0		
7	13	9						
8	4	7						
9	0	1						
10		0						
>10	Without wind	with	w			0		300
	sans vent	avec vent	s.v.	a.v	s.v	a.v.	s.v	a.v
Q mean	2,47	,2	1,33	,2,	0,77	3	0,67	13,

distance from the trace 20°

Q	T= 50 sec.	T= 100 sec.	T= 200 sec.	400 sec.
1	45	94	150	236
2	50	67	106	63
3	29	71	36	1
4	24	40	7	0
5	42	10	1	
6	39	9	0	
7	24	6		
8	19	2		
9	5	1		
10	14	0		
>10				
Q mean	4,16	2,03	1,15	0,68

4. CONCLUSIONS

If we refer to diagram 14, we will clearly see the following two contradictory and fundamental effects for short intervals between interrogation and for the low orbits under consideration:

a) An increase of T is favorable from the point of view only of errors in measurement of distance

b) In the presence of wind, the increase of T leads instead to non-acceptable errors.

We are thus shown the existence of an optimum value of T which, in the case under consideration, will be on the order of 70 sec which corresponds to the best compromise between the effects of a) and b) and for which the error will be distributed approximately one-half over the errors of distance and one-half over the errors due to wind. This value of T which will be as much lower as the random components of the wind are greater, runs the risk of being actually below the value of T which will be necessary for providing interrogation of all the balloons. Under these conditions it will probably be necessary to adopt the "technological" value of T. Under these conditions, the error of localization increases rapidly when we approach the trace and is doubled when we are at

5°instead of 10°from the trace.

Although these fundamental conclusions can already be stated definitely, we are continuing to work on a certain number of computations, among others, to take the random components of the wind into account accurately

This does not present any difficulty of principle since the programs are developed and tested. However, the limitations of the equipment utilized in regard to speed of computation result in a prohibitive expenditure of time in practice. Processing of the programs on the IBM 7040 of CNES is planned but it will be necessary to await completion of this phase before drawing precise definitive conclusions.

CONTINUOUS WIND PARALLEL TO TRACE

PAF

$_i$=2 V D A

$_i$=4 L Q

1 READ R Z E

2 PRINT WITH 5 DECIMALS RC R TAB Z TAB E

3 CALCULATE $V_1=\sqrt{(398599R^3/Z^3)}$

4 CALCULATE $O=R\ (\ COS\ E)^2+(SIN\ E)\sqrt{(1-R^2(COS\ E)^2)}$

5 STATE F=0,087267

6 PRINT WITH 3 DECIMALS TAB F RC

7 STATE V_2=0,0111

8 PRINT WITH 4 DECIMALS TAB V_2 RC

9 STATE T=50

10 PRINT WITH O DECIMAL TAB T RC

11 CALCULATE $L_3=V_2T/2Z\ \ COS\ F$

12 CALCULATE C= ARC COS (O/ COS F)

13 MAKE L_1=-C

14 CALCULATE $L_2\ =L_1+V_1T$

15 " $D_1=Z^2+Z^2/R^2-2Z^2(\ COS\ F\ )\ (COS\ (L_1+L_3)\ )/R$

16 " $D_2=Z^2+Z^2/R^2-2Z^2(COS\ F\ )\ \ (COS\ (L_2-L_3)\ )/R$

17 " $A_1=R(Z^2+Z^2/R^2-D_1)/2Z^2$

18 " $A_2=R(Z^2+Z^2/R^2-D_2)/2Z^2$

19 " G= ARC TG ((A_2COS L_1-A_1COS L_2) / (A_1SIN L_2-A_2 SIN L_1))

20 " H= ARC COS (A_1/ COS (G-L_1))

21 " Q_1=H-F

22 " Q_2=Z 1

E

```
23 CALCULATER Q3=ZG COS F
24    "       Q4=√ (2^2+3^2)
25 PRINT WITH 3 DECIMALS TAB Q2TAB Q 3 TAB Q4 RC
26 MAKE L1 =L2
27 CALCULATE L2=L1+V1T
28 IF L2>C ALLER EN 30
29 GO TO  15
30 MAKE T=T+50
31 IF T>4 ()() GO TO 33
32 GO TO 10
33 MAKE V2=2V2
34 IF V2> 0,o6 GO TO 36
35 GO TO 8
36 MAKE F=2F
37 IF F>0.44 GO TO 39
38 GO TO 6
39 END
40 EXPLANATION OF LETTER SYMBOLS.
```

WIND PARALLEL TO TRACE

R : RADIUS OF BALLOON SPHERE/RADIUS OF ORBIT

Z :RADIUS OF BALLOON SPHERE

E : ELEVATION

V_1 : "$OMEGA_S$" (SATELLITE SPEED)

O : COS O

F : PHI = DISTANCE FROM THE TRACE

V_2 : PARALLEL COMPONENT OF WIND

T : INTERVAL BETWEEN INTERROGATION

L_3 : " α "

C : " γ "

L_1, L_2 :SATELLITE LONGITUDES

D_1, D_2 : DISTANCE SATELLITE-BALLOON

A_1, A_2 : INTERMEDIATE VARIABLE (D_1, D_2)

G : λ^*

H : ϕ^*

Q_1 : ERROR OF LATITUDE IN RADIAM

Q_2 : ERROR OF LATITUDE IN KM

Q_3 : ERROR OF LONGITUDE

Q_4 : OVERALL ERROR

CONTINUOUS WIND PERPENDICULAR TO TRACE

PAF

$_{i}$=2 V D A

$_{i}$=4 L Q

1 READ R Z E

2 PRINT WITH 5 DECIMALS RC R TAB Z TAB E

3 CALCULATE $V_1 = \sqrt{(398599R^3/Z^3)}$

4 CALCULATER $O=R(\cos E)^2+(\sin E)\sqrt{(1-R^2(\cos E)^2)}$

5 STATE F=O, 087267

6 PRINT WITH 5 DECIMALS TAB F RC

7 STATE V_2=0,0111

8 PRINT WITH 4 DECIMALS TAB V_2 RC

9 STATE T=50

10 PRINT WITH 0 DECIMAL TAB T RC

11 CALCULATE $L_3=VXT/2Z$

12 CALCULATE C= ARC COS (O/ COS F)

13 CALCULATE $L_1=-C$

14 CALCULATE $L_2=L_1+V_1T$

15 CALCULATE $D_1=Z^2+Z^2/R^2-2Z^2(\cos(F-L_3))(\cos(L_1))/R$

16 CALCULATE $D_2=Z^2+Z^2/R^2-2Z^2(\cos(F+L_3)09\ \text{Cos}(L_2))/R$

17 " $A_1=R(Z^2+Z^2/R^2-D_1)/2Z^2$

18 " $A_2=R(Z^2+Z^2/R^2-D_2)/2Z^2$

19 " G= ARC TG $((A_2\cos L_1-A_1\cos L_2)/(A_1\sin L_2-A_2\sin L_1)$

20 " H= ARC COS $(A_1/\cos(G-L_1))$

21 " $Q_1=H-F$

22 CALCULATE $Q_2=ZQ_1$

23 " $Q_3=ZG \cos F$

24 " $Q_4=\sqrt{(Q_2^2+Q_3^2)}$

25 PRINT WITH 3DECIMALS Q_2 TAB Q_3 TAB Q_4 RC

26 MAKE $L_1=L_2$

27 CALCULATE $L_2=L_1+V_1T$

28 IF $L_2>C$ GO TO 30

29 GO TO 15

30 MAKE T=T+50

31 IF T>400 GO TO 33

32 GO TO 10

33 MAKE F=2F

34 IF F>0,44 GO TO 36

35 GO TO 6

36 END

37 EXPLANATION OF LETTER SYMBOLS

R :

WIND PERPENDICULAR TO TRACE

R : RADIUS OF BALLOON SPHERE/RADIUS OF ORBIT

Z : RADIUS OF BALLOON SPHERE

E : ELEVATION

V_1 : "$OMEGA_S$" (SATELLITE SPEED)

O : COS O

F : ϕ DISTANCE FROM THE TRACE

V_2 : PENRPENDICULAR COMPONENT OF WIND

T : INTERVAL BETWEEN INTERROGATION

L_3 : " β "

C : " γ "

L_1,L_2: SATELLITE LONGITUDES

D_1,D_2: DISTANCE SATELLITE-BALLOON (d_1,d_2)

A_1,A_2: INTERMEDIATE VARIABLES (D_1,D_2)

G : λ*

H : ϕ*

Q_1 : ERROR OF LATITUDE IN RADIAN

Q_2 : ERROR OF LATITUDE IN KM

Q_3 : ERROR OF LONGITUDE

Q_4 : OVERRALL ERROR

GENERAL WIND - CONTINUOUS AND RANDOM COMPONENTS

```
PAF
i=1 D M A
i=3 F L Q
i=5 V
i=11 I
1 READ R Z E
2 PRINT WITH 3 DECIMALS RC TAB R TAB Z TAB TAB E RC
3 CALCULATE V1= √(398599R^3/Z^3)
4    "      O=R ( COS E) ^2+ (SIN E ) √(1-R^2 (COS E)^2)
5 READ V2
6  "   V4
7  STATE T=50
8 PRINT WITH 3 DECIMALS TAB V2 TAB V4 TAB T RC
9 STATE Fo=0,087267
10 PRINT WITH 3 DECIMALS TAB Fo RC
11 CALCULATE C= ARC COS (O// COS Fo))
12 STATE S=19839
13 STATE (S) =O
14 MAKE S=S+1
15 IF S>19849 GO TO 18
16 STATE (S)=O
17 GO TO 14
18 MAKE Lo=-V1T/2
19 IF Lo<-C GO TO 81
20 CALCULATE L1=V1T/2
```

21 CALCULATE $L_2=V_2T/2Z$ COS F_o

22 " $F_2=V_4T/2Z$

23 PROGRA 153,0

24 STATE V_3=(19741)

25 CALCULATE $L_3=V_3T/2Z$ COS F_o

26 PROGRAM 155,0

27 STATE V_5=(19997)

28 CALCULATE $F_3=V_5T/2Z$

29 IF VARIANT, PRINT WITH 3 DECIMALS TAB V_3 TAB V_5 RC

30 CALCULATE $D_o=\sqrt{}(Z^2+Z^2/R^2-2Z^2(\text{ COS }) F_o-F_2+F_3))$ (COS $(L_o+L_2+L_3))/R)$

31 PROGRAM 153,50

32 STATE V_3=(19741)

33 CALCULATE $L_3=V_3T/2Z$ COS F_o

34 PROGRAM 155,50

35 STATE V_5=(19997)

36 CALCULATE $F_3=V_3T/2Z$

37 IF VARIANT,PRINT WITH 3 DECIMALS TAB V_3 TAB V_5 RC

38 CALCULATE $D_1=\sqrt{}(Z^2+Z^2/R^2-2Z^2(\text{ COS } (F_o+F_2+F_3)) (\text{ COS } (L_1-L_2+L_3))/R)$

39 PROGRAM 151,0

40 STATE B=(19485)

41 IF VARIANT,PRINT WITH 3 DECIMALS TAB B TAB

42 CALCULATE $M_o=D_o+$ B

43 PROGRAM 151,50

```
44 STATE B=(19485)
45 IF VARIANT,PRINT WITH 3 DECIMALS TAB B RC
46 CALCULATE M1=D1+B
47     "     Ao=R(Z^2+Z^2/R^2-Mo^2)/2Z^2
48     "     A1=R(Z^2+Z^2/R^2-M1^2)/2Z^2
49     "     G= ARC TG ((Ao( COS L1 )-A1( COS Lo))/(A1(SIN Lo)-Ao(SIN L1)))
50     "     H= ARC COS (Ao/ (COS ( G-Lo)))
51     "     Q1=Z(H-Fo)
52     "     Q2=ZG COS Fo
53     "     Qo=√( 1^2+2^2 ?)
54 IF VARIANT,PRINT WITH 3 DECIMALS TAB ?1 TAB 2 TAB o RC
55 STATE P=1
56 STATE N=1 S=19839
57 CALCULATE X= o-NP
58 IF X>0 GO TO 63
59 STATE W=(S)
60 MAKE W=W+1
61 STATE (S) =W
62 GO TO 70
63 MAKE N=N+1
64 MAKE S=S+1
65 IF N>10 GO TO 67
66 GO TO 57
67 STATE W=(S)
68 MAKE W=W+1
```

```
69 MAKE (S)=W
70 IF VARIANT,STATE MAKE I1=(19839) I2=(19840) I3=(19841) I4=(19842)
                        I5=(19843) I6=(19844) I7=(19845) I8=(19846)
                        I9=(19847) I10=(19848)I11=(19849)
71 IF VARIANT,PRINT WITH 0 DECIMALS TAB I1TAB I2 TAB I3 TAB I4 RC TAB I5
                TAB I6TAB I7 TAB I8 TAB I9 RC TAB I10 TAB I11 RC
72 MAKE J=J+ Qo
73 MAKE K=K+1
74 IF K>300 GO TO 76
75 GO TO 23
76 CALCULATE Q3=J/300
77 STATE I1=(19839) I2=(19840)I3=(19841) I4=( 19842) I5=(19843) I6=(19844)
                    I7=(19845) I8=(19846) I9=(19847) I10=(19848) I11=(19849)
78 PRINT WITH 0 DECIMALS TAB I1RC TAB I2 RC TAB I3 RC  I4 RC I5RC TAB
                        I6 RC TAB I7 RC TAB I8 RC TAB I9 RC TAB I10 RC
                        TAB I11 RC RC TAB Q3 RC
79 MAKE T=2T
80 GO TO 12
81 MAKE Fo=Fo+0,087267
82  IF Fo>0,44 GO TO 86
83 STATE T=50
84 PRINT WITH 0DECIMALS TAB T RC
85 GO TO 11
86 GO TO  5
END
```

CONTINOUS AND RANDOM COMPONENTS OF GENERAL WIND

R : RADIUS OF BALLOON SPHERE/RADIUS OF ORBIT

Z : RADIUS OF BALLOON SPHERE

E : ELEVATION

V_1 : " ? " (VELOCIDAD OF SATELLITE ROTATION)

V_2 : XONRINUOUA PARALLEL WIND

V_4 : CONTINUOUS PERPENDICULAR WIND

V_3 : RANDOM PARALLEL COMPONENT

V_5 : RANDOM PERPENDICULAR COMPONENT

F_0 : DISTANCE FROM TRACE

F_2 : " β " CONTINUOUS "BETA" F_3 : " β "

L_0, L_1: SATELLITE POSITIONS

L_2 : CONTINUOUS " α "

L_3 : " α "RANDOM

D_0 : DISTANCE $S_1 B_1 = d_1$

D_1 : DISTANCE $S_2 B_2 = d_2$

M_0 : "d_1^* "

M_1 : "d_2^* "

A_0, A_1: INTERMEDIATE VARIABLES

G = " λ^* "

H = " ϕ^* "

Q_1 = ERROR OF LATITUDE IN KM

Q_2 = ERROR OF LATITUDE IN KM

Q_0 = OVERALL ERROR

Q_3 = MEAM ERROR

19839 to 19849	ERROR STORAGE MEMORIES
PROGRAM 153,0	GENERATION OF RANDOM NUMBERS FOR PARALLEL WIND WITH RESUL
	SHOWN IN 19741
PROGRAM 151,0	GENERATION OF RANDOM NUMBERS FOR PERPENDICULAR WIND
	WITH RESULT SHOWN IN 19997
PROGRAM 151,0	RANDOM NUMBERS OF ERRORS OF DISTANCE WITH RESULT
151,50	SHOWN IN 19485